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МАИ

Moscow State Aviation Institute
Aeronautical school
Pilot-vehicle lab

TECHNICAL REPORT

on research

"DEVELOPMENT OF CRITERIA FOR PREDICTION OF HANDLING QUALITIES OF NEW GENERATION OF AIRCRAFT"

(Contract SPC-96-4073)

Princepal investigator

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MAI
Moscow, November 1997

CONTEXT

FOREWORD

The research reported here was accomplished for the United States Air Force by Pilot-vehicle lab. of Moscow State Aviation Institute under contract SPC-96-4073. The program was sponsored by the EOARD of Air-Force department.

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INTRODUCTION

The necessity in creation or modification of standarts to the handling qualities was arisen more than once, each time because of the appearence of the new generation of aircraft. The importance of correct choice in flying qualities was understood by the engineers after the first flights of the airplanes. Expirience in aircraft design accumolated in thirties - forties allowed to develop the reliable methods for calculation of parameters supplied the necessary stability and quaranteered the required handling qualities simultanuosly. The exposed handling qualities criteria basically reflect the peculiarities in manual control typical for aircraft of that period what with taking into account the simularity of created aerodynamics configurations allowed to formulate the first requirements to these criteria at the end of the Second World War. The further expansion of flight envelope and automatization of manual control associated with creation of new generation of aircraft in fifties led to irregularity of many existed flying qualities criteria. The exposed new peculiarities in manual control of these aircraft and their characteristics allowed to create new standarts for flying qualities and their further modification. Because of the simularity of aircraft dynamic characteristics (i.e. classical dynamics), aircraft control devices (column/wheel and central stick, pedals) and displays (instruments) the process of handling qualities design for these aircraft was carried out by use the developed standards based on the previous generation with the further refinements made during the following test phase.

Such approach was simularin US and Russia too and has become inadequate in recent years due to:

1. The incorporation of Fly-by-Wire (FBW) control systems changed the aircraft dynamics considerably.

2. The use of new control devices (including miniwleel, sidestick) and displays (HUD, HDD).

3. The high costs associated with introducing control system modifications in a late phase of the design.

4. Increased requirements to the flight safety and efficiency in fulfilment of the mission.

The empirical way of trial and error used in handling qualities design is non-systematic and obtained results have a rather low level of predictability up to now. It doesn't consider a strong influence of the factors assosiated with peculiarities of highly

augmented aircraft, piloting tasks, and technique. This fact becomes particular evident when choosing the adequate (optimum) silution of the piloting task which should be performed with high precision and with a minimum demand on pilot effort.

The attempt to create the new criteria (for example, equivalent time delay τ_p) taking into account some typical peculiarities of highly augmented aircraft with combination with trial and error technique was unsufficient in many cases. Very offen the results of flight tests didn't correspond to the recommendations obtained by use the criteria included in last version of standards.

In many cases this fact assosiated with the reason that many phenomena arizing in piloting of modern airplane take place in pilot controlled element closed-loop system. The specific peculiarity of this system is the considerable influence of many task variables on pilot behavior and its characteristics. At the same time the proposed new so-called, alternative criteria (for example Neal-Smith criteria) didn't take it into account, and as a concequence have low potentialily in prediction and accuracy.

Because of this circumstane the problem in creation of new criteria and standarts or their modification on basis of new fundamental approach arisen now very sharply.

This approach and criteria have to take into account the modern and future level of augmentation, possibility in appearance of new generation of airplanes, the increased level of requirements in flight safety and efficiency in flight mission and current shortcomings of existed standards. The research in this area were carried out by many investigators. The more perspective way in solution of problem bases on study of pilot-vehicle closed-loop system by use the elements of system analysis.

In [1] there were carried out research on analysis of some reasons of PIO tendency for the highly-augmented vehicles and development of criteria for prediction of this phenomena. It was used aspects of so-called "system approach" in the investigation of problem allowed to expose some new regularities in pilot-behavior in precision manual conrtol tasks and to get the unique criteria for the prediction of handling qualities and PIO tendency. The current research continues the investigation in this area.

There are discussed the context of the problem in standardization of flying qualities and formulated the system approach for its solution.

There are also considered the results obtained by use this approach. Whuch are the following

- the modified criteria for the prediction of handling qualities and PIO tendency,

- the technique for the definition of desired and adequate task performances,

- the results of pilot-vehicle system investigations for the new bank of dynamics configurations, including Have PIO [2] and Have GAS [3] configurations,

- investigation of pilot-vehicle system characteristics in refueling task including the research on influence of different variables, phases of flight, types of aircraft response and development of handling qualities criteria.

There were considered also and some results in optimal control modelling of human-operator behavior and use the modified OCM to a number of piloting tasks.

CHAPTER 1

ANALYSIS OF PROBLEMS IN USE OF THE STANDARDS FOR THE FLYING QUALITIES OF NEW GENERATION OF HIGHLY AUGMENTED AIRCRAFT AND THE WAYS FOR THEIR SOLUTION

The standards for the flying qualities were developed always by the generalyzation of knowledge about the dynamics peculiarities of aircraft created in previous years. Such way in development of standards had some historical stages. Character feature each of them was the unaccuracy of the developed criteria for the new generation or the absence of corresponding criteria reflecting their specific peculiarities.

The considerable expansion of the function of automatization used in fly-by-wire flight control system of the modern aircraft allowed to change considerably the classical aircraft dynamic supposing the maximum accuracy in each piloting task. This purpose of current stage in creation of aircraft can lead for specific combination of different task variables to appearance of new peculiarities and side effects nontypical for the aircraft of the previous generation.

The attempt to define the appropriate dynamics for each piloting task led to idea [4] a necessity to modify the current standards on basis of mission-oriented requirements to the flying qualities. The close princeples were proposed and by authors of current report in [5]. It was demonstrated there that the correct solution in any manual control task depends on understanding of the considerable influence of many task and other pilot-vehicle system variables on characterictics of its system and requires the development of system approach. The use of this approach to the problem of standardization of flying qualities has to allows to elimitate the conflict between the new features on aircraft dynamics and used criteria, to expose the ways for modification of standards and to develop the new criteria. The necessity of such approach can be grounded by the analysis of used requirements and handling qualities criteria.

This analysis is necessary also for the definition of the tasks which has to be decided in modification of standards and development of new handling qualities criteria.

1.1. Analysis of principles of standarts to the handling qualities

Used standards to the flying qualities [6,7] bases on the same principles supposing the devision of requirements according to:

- classes of aircraft;
- phases of flight;

- pilot rating levels.

For some reason these principles causes the problems.

The devision of airplanes on classes supposses that the airplanes of considered class have the common dynamic features. Such principle causes the problem in evaluation of flying qualities for new types of vehicles, such as ultralight and aerospace vehicles, airships. In general the features of these vehicles don't correspond to the feafures of aircraft corresponded to weight or manoeuvrebility defined in current standarts.

The requirements to the handling qualities are defined in suggestion of considerable difference between the values of short-period and phugoid frequencies. This circumstance is one of the problem in use of recommendations for ultralight airplane characterized by low velocities. In that case the values of frequencies in phugoid, $\omega_{ph} = \frac{g}{V}\sqrt{2}$, and short period motions $\omega_{sp} = V \cdot F$ (where F is a function of aerodynamic characteristics) begin to approach each other. According to the weight factor the aerospace vehicles "Buran" and Space Shuttle are close to the 3-4 classes of aeroplanes. However dynamically the characteristics of these vehicles don't correspond to them. They have unusual combination in path and angular responses: the sluggish response in path motion (more sluggish than the responses of airplanes related to 3÷4 classes) and rapid reaction in angular motion, which is more typical for 1-2 classes of aircraft. This combination didn't allow to apply to requirements used for 3-4 classes of airplanes for the choice of flying qualities of aerospace vehicles.

Some new types of aircraft (for example airship) have complitly new type of responses no corresponded to the aircraft of any class. It means that many recommendation of current standarts can not be used for the choice of flying qualities for these aircraft.

In principle there are not ground to doubt that in fucture can appear any new type of vehicles characterized by unusual dynamics.

All these circumstances require to develop more flexible approach taking into account the possibily of appearance such vehicles.

The current standarts suppose the difference in requirements for the three flight phases (A, B, C). The phase A combines all precise tracking tasks. There are the following

- air-to-air - tracking task,

- dive bombing,
- formation flight,
- refueling,
- terrain following.

Each of these tasks is characterized by the different coordinate x(t) of outer loop (see table 1.1) defined the aim of control, the specific set of other coordinates, controlled element dynamics, $W_c = \frac{x(t)}{c(t)}$, and other tasks variables too. The details of this dependence see in [1].

Table 1.1

Task	The coordinate of outer loop	The additional inner coordinates closed by pilot
air-to-air tracking	$\varepsilon = \theta + \Delta H / L$ (L - distance between aircraft and aim)	-
refueling (final stage)	$\varepsilon L = \theta L + \Delta H$	-
formation flight	ΔH, ΔX	$\Delta \dot{H}, \Delta \theta$
terrain following	ΔH	$\dot{H}, \theta$
flare (final stage)	H_p - altitute at the pilot station	θ

Each piloting task is accomponied by the different accuracy in its fulfilment, pilot workload and pilot ratings. There is shown in [1] that the flying qualities of the same aircraft are evaluated differently for the different piloting tasks. As an example, there are shown on fig.1.1 the results of investigation of different tracking task: pitch control and air-to-air tracking tasks of the same dynamic configuration. In pitch control tracking task the flying qualities were evaluated with pilot rating PR = 3, and in air-to-air tracking task-with PR = 6.5. The fulfilment of the last tracking task is accompanied by increase of resonance peak of closed-loop system and pilot lead compensation (see fig.1.1). The transformation of measured characteristics takes place and in case of adding of the secondary manual control task, in case of change of input spectrum or any other task varibles. All these circumstances require to revise the principle of

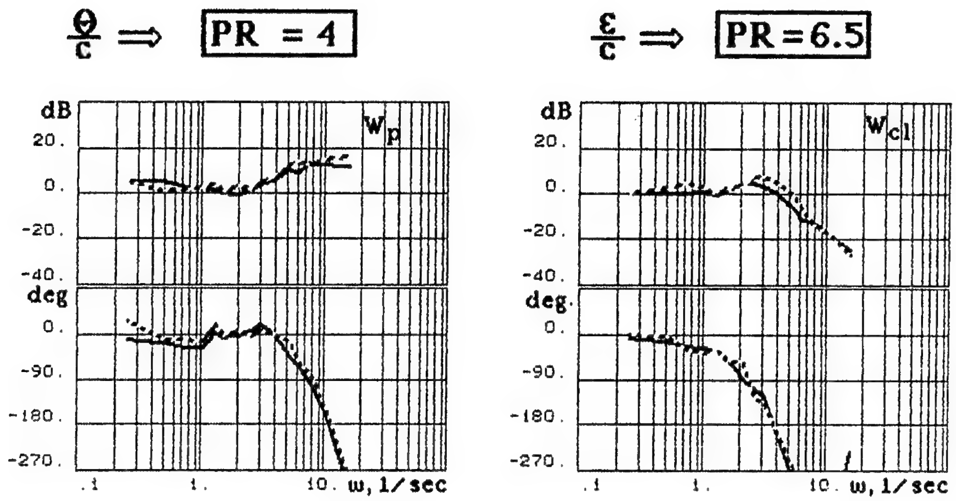


Fig.1.1. Influence of piloting task on $W_p(jw)$

standardization of flying qualities and development of new approach, tacking into account the plirality of piloting tasks and influence of their variables.

The third and last basic principle in standardization is the difference in requirements for the levels of ratings. This principle supposes the use of specialized scales. The widely used scale for evaluation of flying qualities is Cooper-Harper scale. Its shortcoming is the absence of any concrete instructions about the key parameters: task performances and pilot compensation, defined the values of ratings. It leads to considerable variance in pilot ratings, dependent on pilots or engineers understanding about the meanings of these parameters. The investigation of tracking task carried out in [1], where the permissible level of error was supposed as a task performance, demonstrated the considerable influence of this parameter on all pilot-vehicle system characteristics including pilot rating (see table 1.2).

Table 1.2

d, sm	0.5	1.0	1.5	2.0
$\varphi_{p_{max}}$, deg	45	40	27	12
r, dB	8.15	7.53	6.3	2.3
PR	8.5	8	6	3.5

This result demonstrates the neccessity in determination of key parameters: task performanses and pilot compensation, for each piloting task. Except this remark the general conclusion of the considered analysis is the necessity in development of new flexible approach to the standardization allowed to get the recommendations to flying qualities from the single positions for the different class of airplane and piloting tasks.

1.2. Analysis of criteria for evaluation of aircraft flying qualities

1.2.1.The approaches in development of criteria for prediction of flying qualities

The choice of aircraft and its flight control system parameters (parameter "a") is carried out by use the requirements to the flying qualities (so-called flying qualities criteria): F(x); $a \in V_X$. The parameters "x" include parameters "a" and parameters of pilot-vehicle system "b". As a rull the criteria are defined as the limit values of flying qualities F(x). The approach to these limits is accompanied by the first and the second

levels of pilot ratings. There are the different ways in the development of aircraft flying qualities. The basic ways are shown in table 1.3.

The criteria for evaluation of flying qualities Table 1.3

Current criteria F	Problems
1. Criteria F are requirements to: a. Parameters of controlled element dynamics describing function $W_c(j\omega, a)$ or their combination $a = f(a_i, a_j)$ b. Parameters of time response $a = f(x(t))$ c. Generalyzed parameters a* $a^* = f(W_c(j\omega))$	- poor accordance between the predicted and real pilot ratings
2. Criteria F(b) defined by the parameters of pilot vehicle system ("b")	- poor reliability in prediction of flying qualities, - inpossibility to evaluate the influence of many variables of pilot-vehicle system, - simplified representation about optimal ("best") controlled element dynamics, - the absense of criteria for the prediction of PIO tendency.

Basicaly the current criteria supposes the simularity in type response and its nearest in responses to classical aircraft dynamics. Because of this suggestion many of requirements are defined in US standards in terms of parameters of well-known transfer function (for example short period drequency ω_{sp}, damping ratio ξ_{sp}) or combination of the parameters (for example force gradient F^n, or parameter ω^2 / n_y^{α}). Simularity in time response for many aircraft of different classes defined the approach used in stardards where the time response parameters are the criteria (see [17]). The difference between the classic aircraft dynamics and dynamic of highly augmented aircraft lead to considerable problem in use of criteria developed for aircraft with traditional dynamics. For deeper understanding of the problem there are discussed below briefly some parameters in highly augmented aircraft dynamic.

1.2.2. The brief analysis of some peculiarities in hinghly augmented aircraft dynamics

During the last period the highly augmented (or superaugmented) flight control

system (FCS) were installed on board of new generation of aircraft (for example, Space Shuttle, X-29, F-22 (USA), or Buran, TU-204, SU-37 (Russia)). The high potentialities of such kind of system increased the interest in design of new types of flight control system. The preliminary investigations of them and exposed features in developed highly augmented flight-control system allow to generelyze the peculiarities typical for all these systems. There are the following.

1. The considerable potentiality in change of airframe dynamics and new types of aircraft responses.

2. Nontraditional sideffects assosiated with the functioning of FCS.

The new potentialities in change of aircraft dynamics

The destination of FCS for the new generation of aircraft has changed considerably. Instead of the systems supplied the improvement of handling qualities (case of low level of augmentation) FCS transform them in system supplied the necessary handling qualities. Such function of the modern system led to appearance of variaty reayzing the new types of responses in linear range of their functioning.At least there are several of them discussed below.

The transformation of aircraft dynamics by use the direct force control. The use of direct force control surfaces allows to realise the new forms of motion (see table 1.4).

The new modes of aircraft with direct force control surfaces Table 1.4.

№ of modes	Longitudinal motion	Lateral motion
1	θ = variable α = const	Ψ = variable $\beta = 0$ $\varphi = 0$
2	φ= variable θ = const	β = variable $\Psi = 0$ $\varphi = 0$
3	$n_z = 0$; $\gamma = 0$ θ = variable α = variable	Ψ = variable β = variable $n_y = 0$

These new modes can be realize by the different ways. In table 1.5 there are shown several transfer functions for classical aircraft and aircraft with DLC. In the lat case

there is supposed that crosscoupling between the elevator and direct lift control channel is used to get the first and the second type of modes.

The comparison of classic and DLC dynamics

Table 1.5

№ of modes	Dynamics with DLC	Classical dynamics
1	$\frac{\vartheta}{c} = \frac{K_c^2 M_\delta}{s(s - M_q)}$ $\frac{\varepsilon}{c} = \left(s + \frac{V}{L}\right) \frac{K_c M_\delta}{s^2 (s - M_q)}$	$\frac{\vartheta}{c} = \frac{K_c M_\delta (s - Z_W)}{s(s^2 + 2\xi_{sp}\omega_{sp} s + \omega_{sp}^2)}$
2	$\frac{\theta(s)}{c(s)} = 0$ $\frac{\varepsilon}{c} = \frac{1}{L} \frac{H(s)}{c(s)} = \frac{\frac{1}{L} K_c H_Z^{\delta_{DLC}}}{s(s - Z_W)}$	$\frac{\varepsilon(s)}{c(s)} = \frac{K_c M_\delta (s^2 - Z_W s - Z_W \frac{V}{L})}{s^2 (s^2 + 2\xi_{sp}\omega_{sp} s + \omega_{sp}^2)}$

Here ε(s) is an angle of sight $\varepsilon = \theta + H/L$, L is a distance between the aircraft and aim. The transfer functions of table 1.5 are obtained without taking into account the actuator dynamics the aerodynamic effect of elevator and distance between the pilot and c.g.

The shown transfer functions demonstrate the high potentrality to change the aircraft dynamics with help of DLC. It can be approached to $W_c = k/p$ in wide frequency range in pitch control (mode 1) or in angle of sight control (mode 2) in case when $-M_q$ and $-Z_W$ more then 1. The efficiency of angle of sight control in case of mode 2 considerably depends on the efficiency of DLC surface ($n_Z^{\delta_{DLC}}$).

Potentialities of augmentation with traditional control surface for realization of necessary flying qualities and new type of responses. The linearized structure of flight control system is shown on fig.1.2. Here $W_{pr}(s)$ is the transfer function of prefilter, W_c - aircraft transfer function, W_f and W_{fB} are the corresponding filters in closed-loop system, W_a - transfer function of actuator.

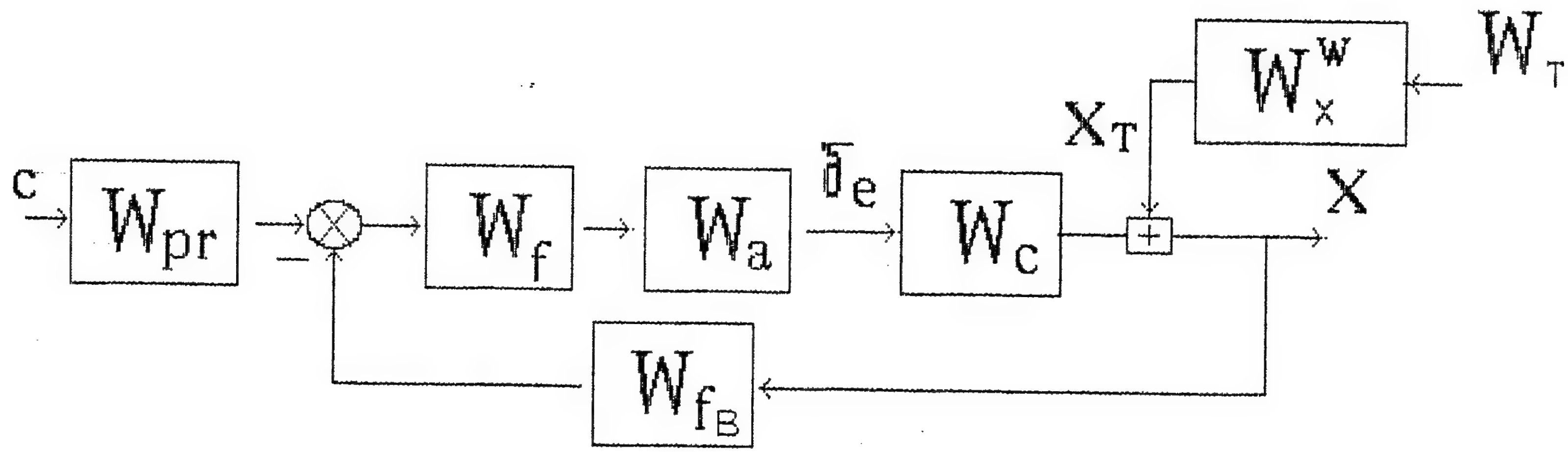


Fig.1.2. Linearized flight control system of highly aygmented aircraft

The closed-loop transfer functions for coordinates x_1 and x_2 are the following:

$$\frac{x_1}{c} = \frac{W_{pr}}{W_{fB}} \left\{ \frac{W_f W_{fB} W_a W_c^{x_1}}{1 + W_f W_{fB} W_a W_c^{x_1}} \right\} \tag{1.1}$$

$$\frac{x_2}{c} = \frac{x_1}{x} \left\{ \frac{W_c^{x_2}}{W_c^{x_1}} \right\} \tag{1.2}$$

The potentialities and consequences from high level of automatization is evaluated below for high values of coefficients $|W_f|$ >> 1. For such case the transfer functions (1.1) and (1.2) transform to the following:

$$\frac{x_1}{c} \cong \frac{W_{pr}}{W_{fB}} \tag{1.3}$$

$$\frac{x_2}{c} \cong \frac{W_{pr}}{W_{fB}} \left\{ \frac{W_c^{x_2}}{W_c^{x_1}} \right\} \tag{1.4}$$

There is seen that for considered case the controlled dynamics for the tracking coordinate (x_1) is defined by the filters and practically doesn't depend on the aircraft dynamics. These filters are defined the dynamics of intermediate coordinate too. In case of nontraditional response of coordinate x_1 intermiediate coordinate will be also nontraditional too.

Main goal in choice of FCS structures and parameters is to supply flying qualities by approach them to the best controlled element dynamics.

There are considered the several versions of such means. Some of them causes the appearance of new types of responses.

<u>The improvement of flying qualities</u> by considerable increase of damping. The considerable increase of damping (ξ_{sp}) leads to the real roots in short period motion.

In that case $W_c = \frac{\theta}{c} = \frac{K_c(p - Z_W)}{s(s - p_1)(s - p_2)}$. For root p_1 (or p_2) close to Z_W this transfer function has the following form: $W_c = \frac{\theta}{c} = \frac{K_c}{s(s - p_2)}$. For high values of p_2 this transfer function approaches to integral. Such way in improvement of flying qualities cases the aperiodic type of time responses in anglurar velocity q and angle of attack motions.

The improvement of flying qualities by use of Rate-control-attitule-hold (RCAH) type of system.

This system can be represented with help of block-scheme shown on fig.1.2 where

$$W_n = 1,\ W_{fB} = 1,\ W_f = \frac{K_q(p + 1/T_q)}{p} \text{ and } x = \omega_z. \tag{1.5}$$

For this system the transfer function of aircraft in pitch control is the following

$$W_c = \frac{\theta}{c} = \frac{K_c(s + 1/T_q)}{s(s^2 + 2\xi_n\omega_n s + \omega_n^2)} \tag{1.6}$$

where zero $1/T_q$ is the parameter of filter W_f. The increase of this parameter (when $1/T_q \geq Z_W$) allows to decrease the overshoot in time response $\omega_z(t)$ considerably (see fig.1.3). For example, for the same values of parameters ω_n and ξ_n (ω_n = 5 1/s, ξ_n = 0.7) the overshoot in $\omega_z(t)$ for aircraft with RCAH type of system supplied $1/T_q$ = 3.5 in 3 times less in comparison with conventional dynamics defined by - Z_W= 1.25. The increase of $1/T_q$ allows also to get the slope of W_c equal to - 20 dB/dec in wider frequency range. However because of the dependence between the parameters ω_n, ξ_n and $1/T_q$ for RCAH type of system [3]

$$\omega_n = \left(2/T_q\right)\xi_n. \tag{1.7}$$

the considerable increase of the $1/T_q$ can lead to decrease of ξ_n and increase of overshoot. Thus the choice of all parameters $1/T_q$, ω_n and ξ_n has to have the compomize. One of the version of RCAH type of system is the extended RCAH for which the prefilter $W_p = \frac{s + a_1}{s + a_2}$, and $a_1 > a_2$. The difference in values between $1/T_q$

and $-Z_W$ causes to the change in responses on other coordinates too (see fig.1.4-1.6). It is the consequence of the change in the corresponding transfer functions.

For example for aircraft with RCAH system the angle of attack α(s) and altitude transfer functions $H_{c.g.}(s)$ at the anter of grafity are the following

$$W_c^{\alpha} = \frac{\alpha(s)}{c(s)} = \frac{(s+1/T_q)}{(s-Z_W)} \frac{K_c}{(s^2+2\xi_n\omega_n s+\omega_n)} \tag{1.8}$$

$$W_c^{H} = \frac{H_{c.g.}(s)}{c(s)} = \frac{(s+1/T_q)}{(s-Z_W)} \frac{K_c n_{\alpha} g}{(s^2+2\xi_n\omega_n s+\omega_n^2)} \tag{1.9}$$

These frequency response characteristics for this system is differed in comparison with classic dynamics in frequency range $-Z_W < \omega < 1/T_q$. Particullary the slope of amplitude $\left|\frac{H_{c.g.}(j\omega)}{c(j\omega)}\right|$ in this range is close to - 60 dB/dec what increase the difficulty in altitude control considerably.

The considerably higher difference in response takes place for the attitude control - attitude hold (ACAH) type of system. This type of response can be realized by the different ways

a. By use of prefilter $W_{pr} = \frac{Tp}{Tp+1}$ in combination with RCAH or conventional dynamics. In this case the aircraft dynamics for pitch angle is the following

$$W_c^{\theta} = \frac{\theta(s)}{c(s)} = \frac{K_c T(s+1/T_q)}{(Ts+1)(s^2+2\xi_n\omega_n s+\omega_n^2)} \tag{1.10}$$

where $1/T_q$ is not equal to Z_W in general case.

The usage of prefilter $W_{pr} = \frac{Tp}{Tp+1}$, allowed to change the aircraft dynamics in altitude and angle of attack motion considerably. For case when zero in W_c^{θ} is defined by Z_W the tranfer functions $W_c^H = \frac{H(s)}{c(s)}$ and $W_c^{\alpha} = \frac{\alpha(s)}{c(s)}$ are the following

$$W_c^{H} = \frac{K_c T n_{\alpha} g}{(Ts+1)s(s^2+2\xi_{sp}s+\omega_{sp}^2)} \tag{1.11}$$

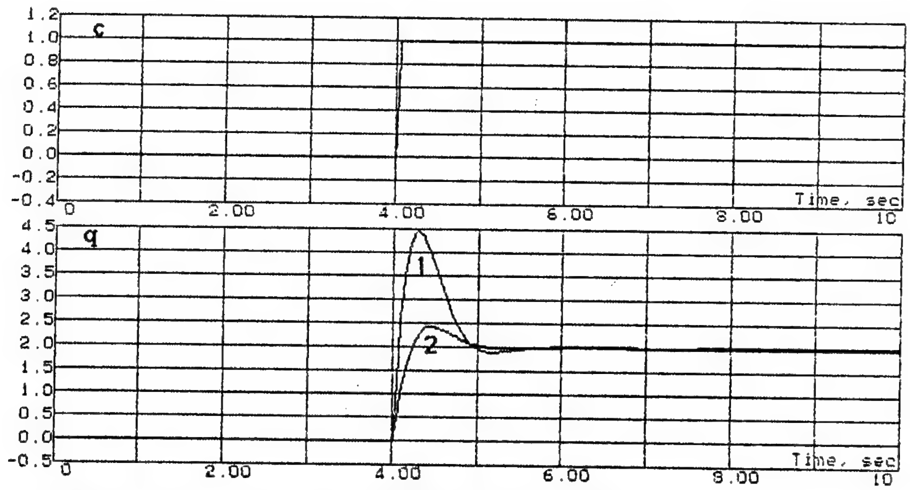


Fig.1.3. Pitch rate time response q(t) ($W_{pr}=1$)
1 - 1/Tq = -Zw = 1.25
2 - 1/Tq = 3.5, -Zw = 1.25

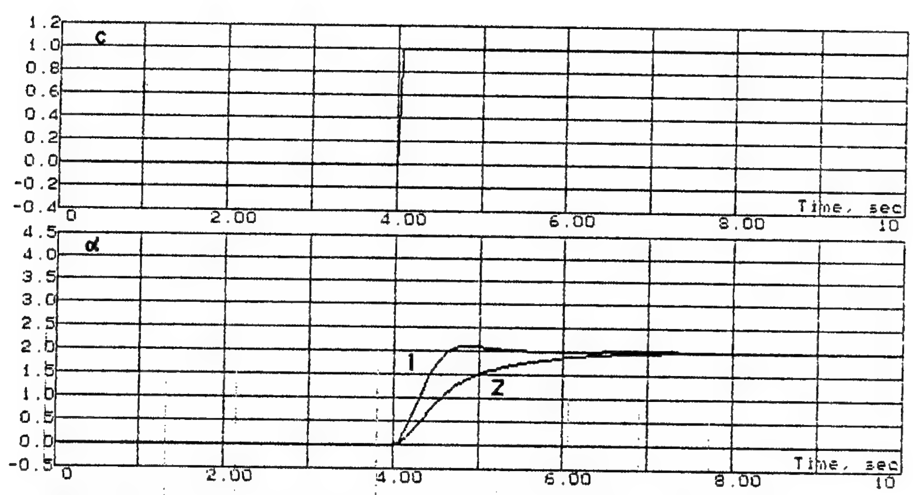


Fig.1.4. Angle of attack time response α(t) ($W_{pr}=1$)
1 - 1/Tq = -Zw = 1.25
2 - 1/Tq = 3.5, -Zw = 1.25

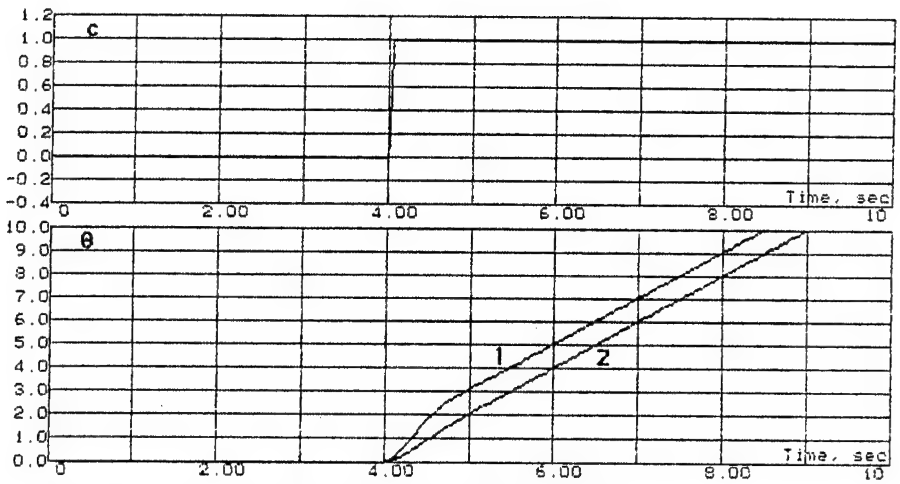


Fig.1.5. Pitch time response $\theta(t)$ ($W_{pr}=1$)
1 - $1/T_q = -Z_w = 1.25$
2 - $1/T_q = 3.5$, $-Z_w = 1.25$

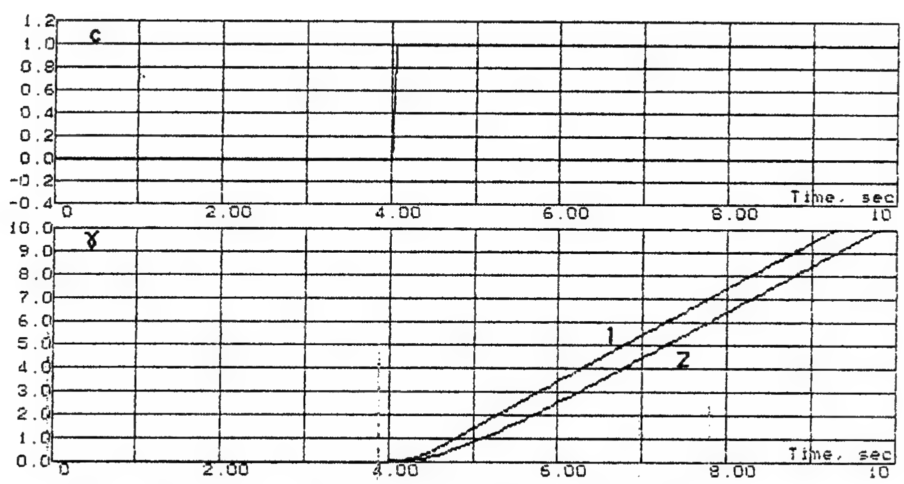


Fig.1.6. Path angle time response $\gamma(t)$ ($W_{pr}=1$)
1 - $1/T_q = -Z_w = 1.25$
2 - $1/T_q = 3.5$, $-Z_w = 1.25$

$$W_c^{\alpha} = \frac{K_c Ts}{(Ts+1)(s^2 + 2\xi_{sp}\omega_{sp}s + \omega_{sp}^2)} \qquad (1.12)$$

The shown on fig.1.7-1.10 responses $\omega_z(t)$, θ(t), γ(t) and α(t) demonstrate their considerable difference in comparison with conventional dynamics.

The decrease of order in transfer funcion for altitude (W_c^H) allows to suppose that the usage of ACAH system for precise path control can be accompanied by considerable decrease in pilot workload and accuracy in control. For case when zero in W_c^{θ} determines by the parameter $1/T_q$ the equations (1.11) and (1.12) transform in the following

$$W_c^H = \frac{K_c T g n_{\alpha}(s + 1/T_q)}{(Ts+1)(s - Z_W)s(s^2 + 2\xi_n\omega_n s + \omega_n^2)} \qquad (1.13)$$

$$W_c^{\alpha} = \frac{K_c T(s + 1/T_q)}{(Ts+1)(s - Z_W)s(s^2 + 2\xi_n\omega_n s + \omega_n^2)} \qquad (1.14)$$

The difference in these two groups of transfer functions canses the difference in time responses (see fig.1.7-1.10). For the last case the potentialy in improvement of altitude dynamics by use as the prefilter $W_{pr} = \frac{Tp}{Tp+1}$ is deterioreted. It can be improved by use the combination of ACAH + extended RCAH system for which filter $W_f = \frac{Tp}{Tp+1}\frac{p+a_1}{p+a_2}$, where $a_1 \approx -Z_W$ and $a_2 \equiv 1/T_q$.

b. By use the pitch feedback.

This way in organizing of ACAH of responce has the similar effects as the previous, but requires the considerable feedback gain coefficients to get the results.

The analysis of the tendency in development of FCS design allowes to suppore that in the future the attempts on improvements of flying qualities with goal to their optimization for each piloting task will continue.

The task of optimization of controlled element dynamics (W_c^{opt}) was decided in [9] and briefly was considered in [1]. There is shown that W_c^{opt} is a function of input spectral density ($S_H(\omega)$) and pilot limitation parameters (time delay τ and level of

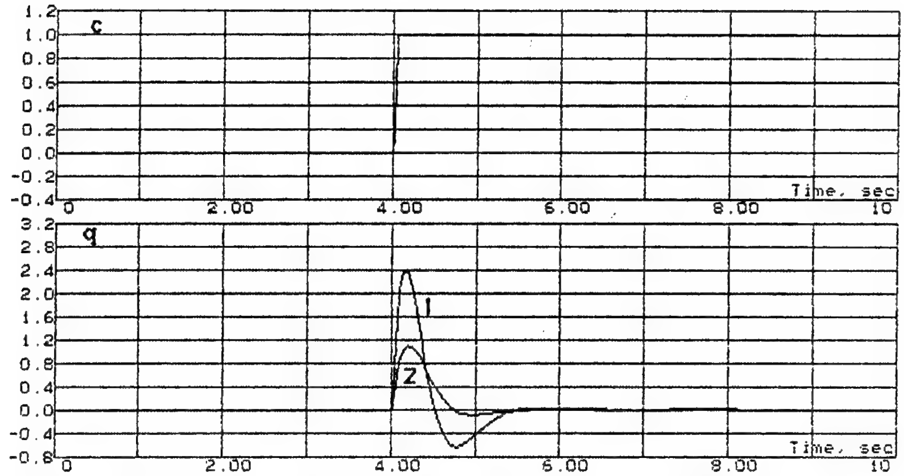


Fig.1.7. Pitch rate time response q(t) ($W_{pr} = \frac{0.2s}{0.2s+1}$)
1 - $1/Tq = -Zw = 1.25$
2 - $1/Tq = 3.5$, $-Zw = 1.25$

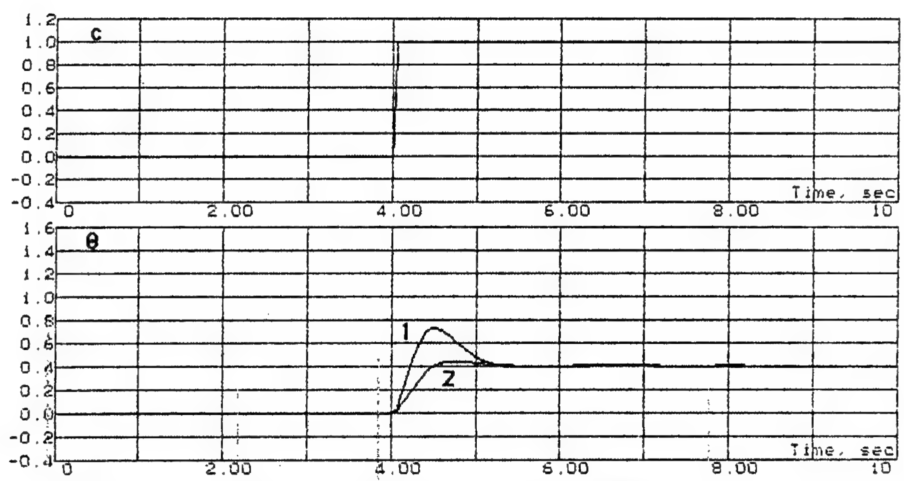


Fig.1.8. Pitch time response θ(t) ($W_{pr} = \frac{0.2s}{0.2s+1}$)
1 - $1/Tq = -Zw = 1.25$
2 - $1/Tq = 3.5$, $-Zw = 1.25$

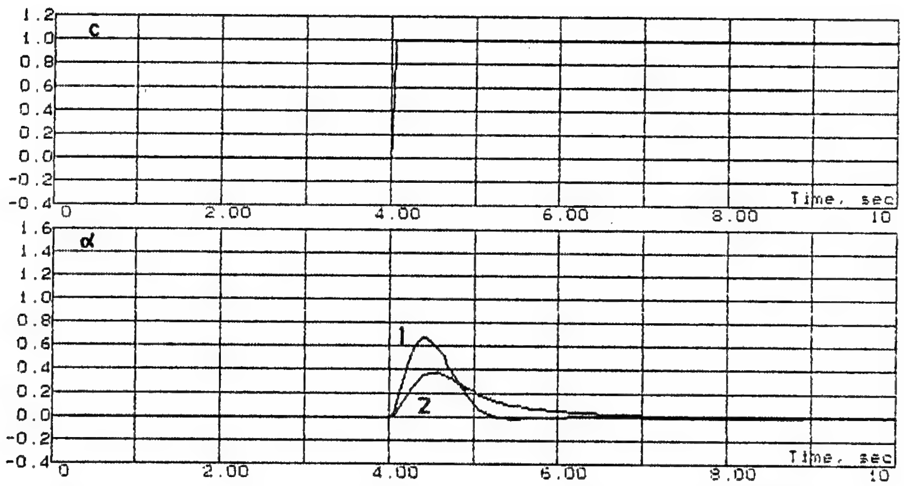


Fig.1.9. Angle of attack time response $\alpha(t)$ ($W_{pr}=\frac{0.2s}{0.2s+1}$)
1 - $1/Tq = -Zw = 1.25$
2 - $1/Tq = 3.5$, $-Zw = 1.25$

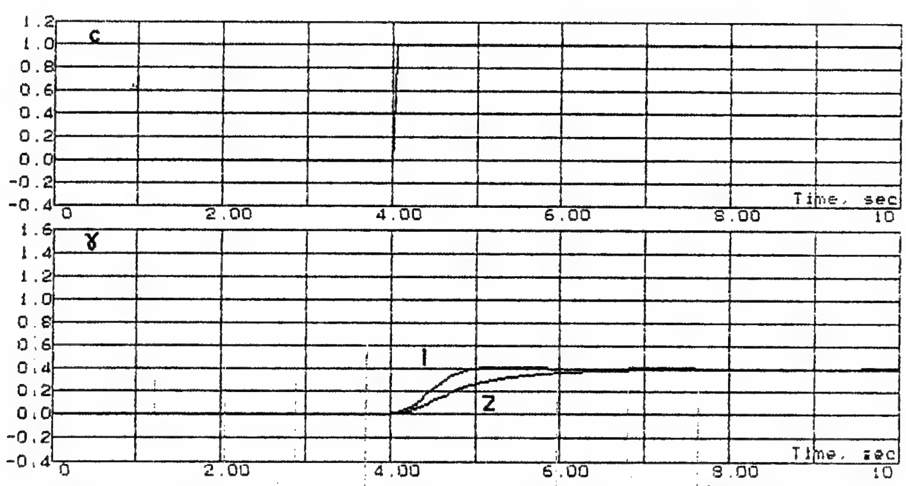


Fig.1.10. Path angle time response $\gamma(t)$ ($W_{pr}=\frac{0.2s}{0.2s+1}$)
1 - $1/Tq = -Zw = 1.25$
2 - $1/Tq = 3.5$, $-Zw = 1.25$

normalized spectral density $\bar{S}_{n_e n_e}$), i.e. $W_c^{opt} = f(S_{ii}, \tau, \bar{S}_{n_e n_e} = K_{n_e})$. Because each piloting task is characterized by the specific spectral density the W_c^{opt} is a function of piloting task too. The optimal controlled element dynamics for the first and third order of input spectral density are the following

$$W_c^{opt} = \frac{K_c(s+1/\tau)}{(s+1/\omega_i)(s+1/\omega_\tau)} \text{ for } S_{ii} = \frac{K^2}{\omega^2 + \omega_i^2} \tag{1.15}$$

where the approximate equations for K_τ and ω_τ are the following

$$\omega_\tau = \frac{2}{\tau}\sqrt{\frac{\tau}{\pi K_{n_e}}} \; ; \; K_\tau = \frac{1 + \frac{\tau}{\pi K_{n_e}} - \sqrt{\frac{\tau}{\pi K_{n_e}}}}{\omega_i \tau \frac{\tau}{\pi K_{n_e}}}$$

$$W_c^{opt} = \frac{K_c(s+a_1)(s+a_2)(s+a_3)}{(s+b_1)(s+b_2)(s+b_3)(s+b_4)} \text{ for } S_{ii} = \frac{K^2}{(\omega^2 + \omega_i^2)^2} \tag{1.16}$$

where a_1 a_2 b_1 b_2 b_3 are the function of parameters ω_i, τ, K_{n_e}. On fig.1.11 there are shown the frequency and time response characteristics for these transfer function.

If we will suppose that these transfer functions are the optimal controlled element dynamics for pitch angle control than the time response for other coordinate will be nontraditional. On fig.1.12-1.13 there are shown the time responses of pitch and angle of attack for the cases when optimal dynamics in pitch motion corresponds to (1.15) or (1.16).

1.2.2.2. The nontraditional sideeffects assosiated with the functioning of FCS

There are discussed below 3 sideeffects accompaning the process of aircraft control with highly augmented FCS:

- increased time delay,
- considerable influence of nonlinearities,
- influence of augmentation on equivalent input spectrum.

The incresed time delay. The character feature of highly augmented aircraft is the wide usage of different filters, computers realized the complex algorithms and flight

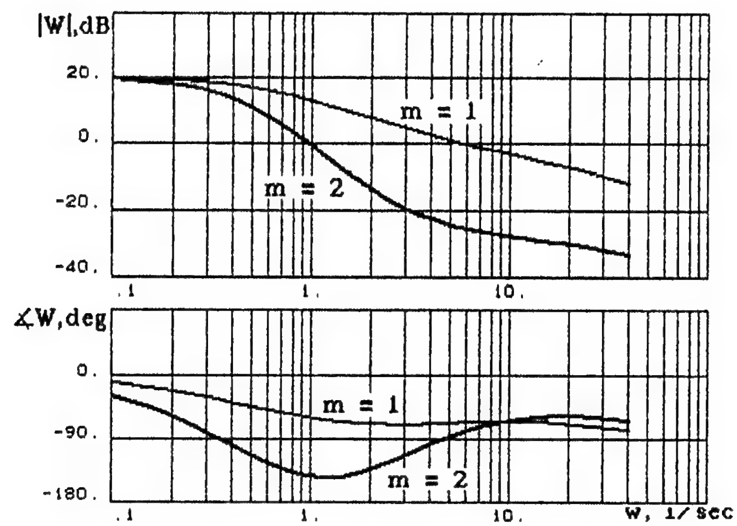


Fig.1.11. Optimal dynamics $W_c^{opt}(jw)$ for $S_{ii} = \frac{k}{(w^2+0.5^2)^m}$

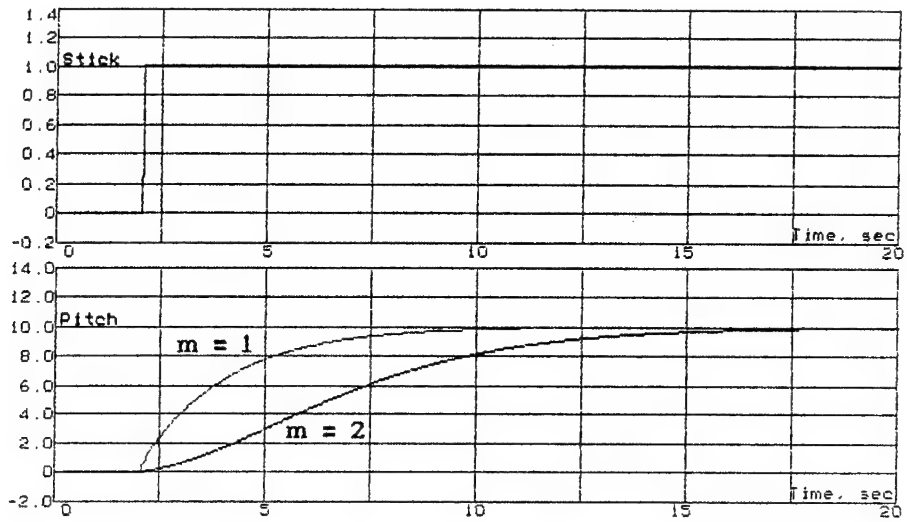


Fig.1.12. Pitch angle time response of W_c^{opt}

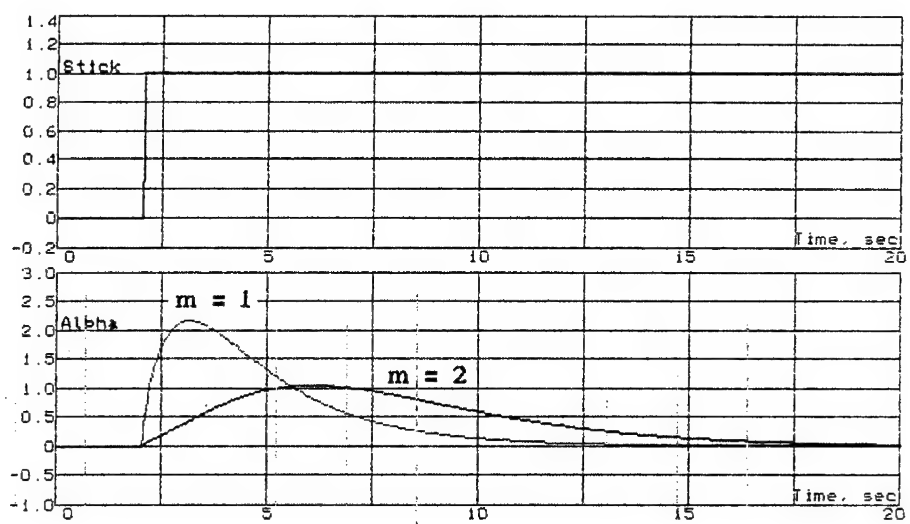


Fig.1.13. Angle of attack time response of W_c^{opt}

control system laws. As a consequence it leads to increase of complexity of the model of aircraft motion to its difference from the second order model described the angular motion of aircraft preveus generation rather accuratily. The difference can be taked into account by the following equation

$$W_{c_э} = W_c^э \prod_i W_i$$

where $W_c^э$ - the equivalent transfer function of conventinal type,

W_i - the transfer functions of different filters.

The effect of ellement $\prod_i W_i(s)$ in middle frequency range can be taked into account in many cases with help of time delay element

$$\prod_i W_i(8) \cong e^{-s\tau}$$

For the highly augmented vehicle this equivalent time delay has rather considerable values: 0.18 s for Space Shuttle and 0.26 Buran.

<u>The considerable influence of nonlinearities</u>. There are different nonlinearities can take place in FCS. At least two of them the ratlimit, $\dot{\delta}_{max}$, and position limit δ_{max} can cause the dramatic effects in control process. Such considerable influence is assosiated with high values of feedback gain coefficients and considerable increase of signals coming to limiters. In linear sense the rate limit leads to considerable increase of phase delay and decrease of damping of equivalent controlled element dynamics (see fig.1.14 from [1]). The additional investigation demonstrated the considerable influence of aircraft flying qualities on the effects of this limiter. For example aircraft with considerable bandwith supplied by the FCS and allowed to realize high controlled element coefficients can cause the considerable deterioration control process and increase of PIO tendency. These negative effects can be more significant in comparison with aircraft with higher phare delay and lower value of bandwidth. In partcular this phenomena was investigated in process of fulfilment of tracking task when input signal

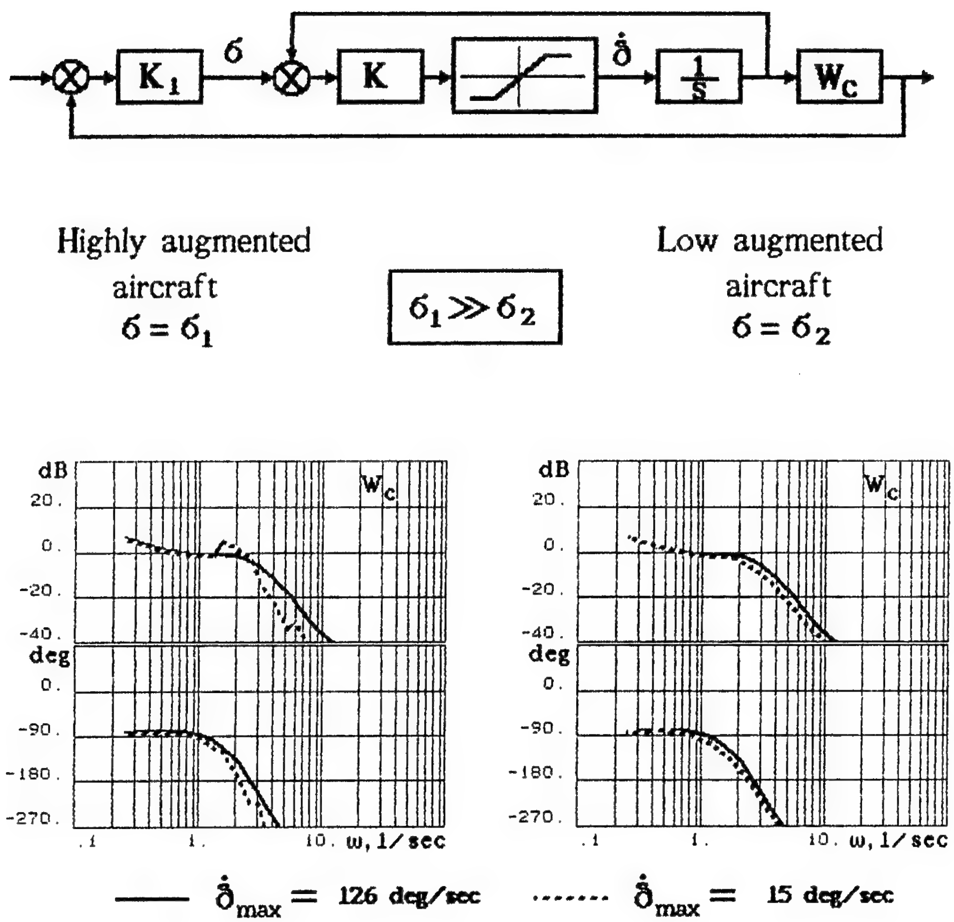


Fig.1.14: The influence of rate limit

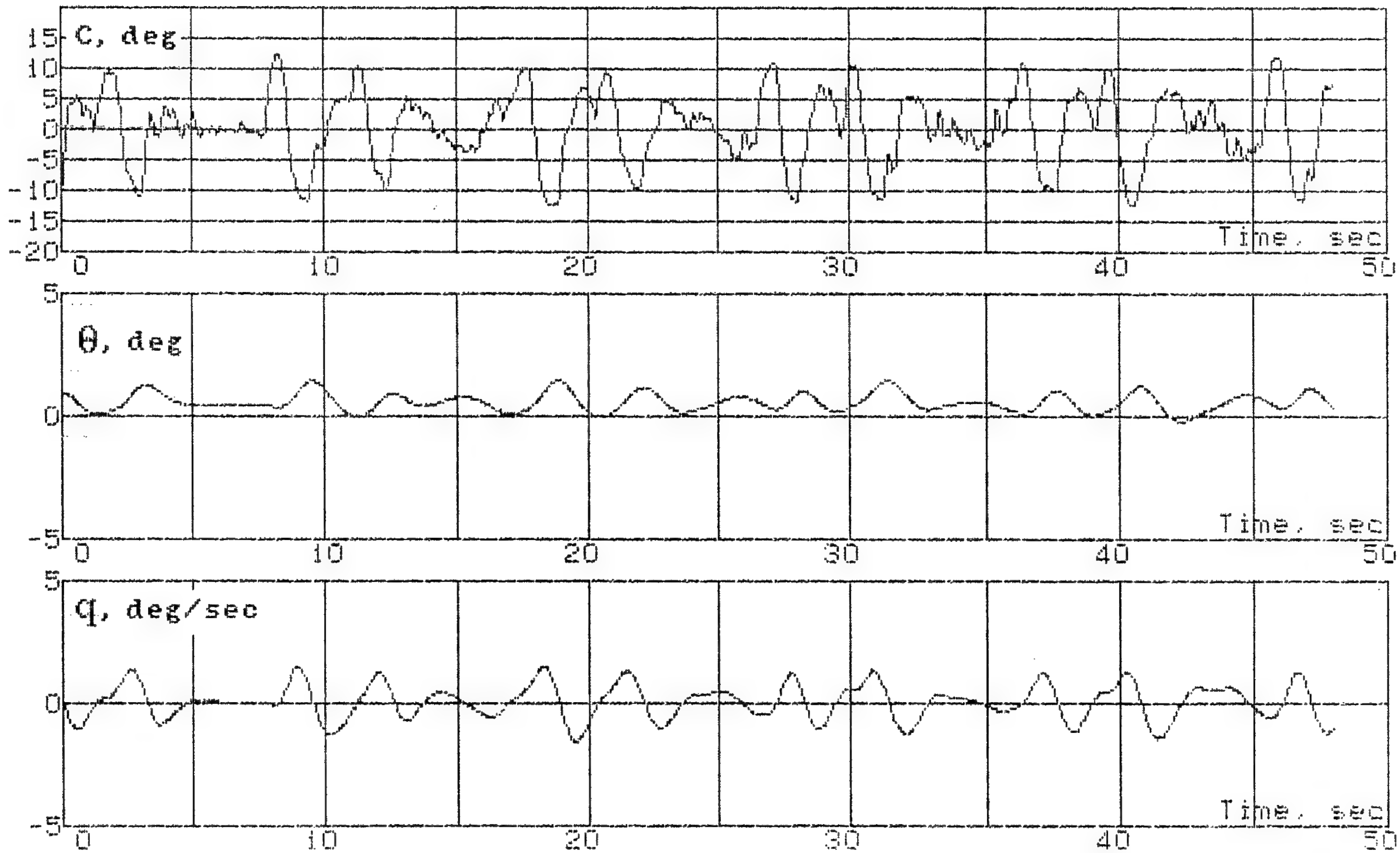


Fig.1.15 Time responses for aircraft with decreased bandwidth w_θ

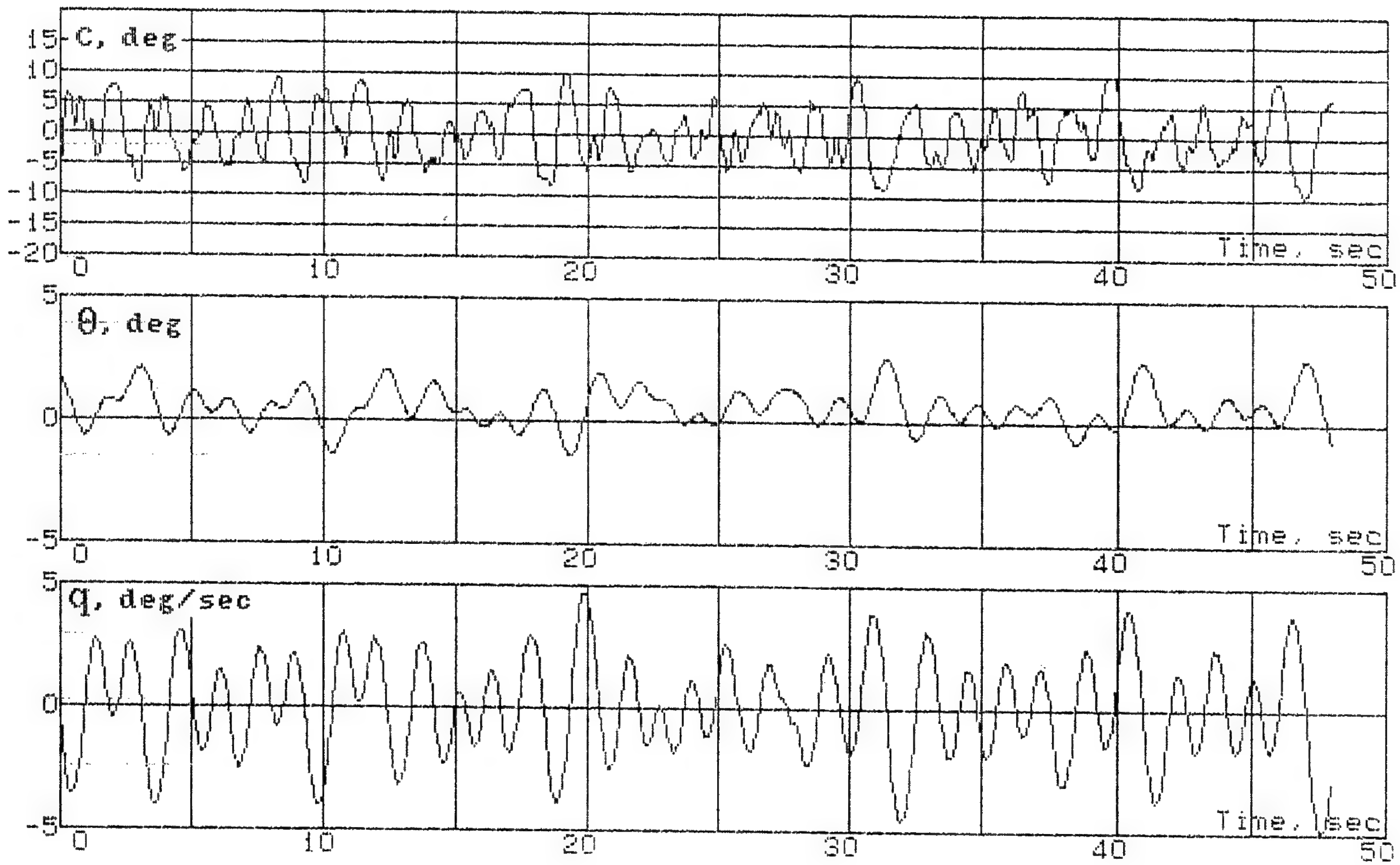


Fig.1.16 Time responses for aircraft with increased bandwidth w_θ

had the following garmonic form.

$$i(t) = \begin{cases} A/2\ (1-\cos\omega_1(t-t_0) & t-t_0 < 2\pi T_1 \\ 0 - \textit{in another case} \end{cases}$$

where

$$\omega_1 = \frac{1}{T_1}$$

t_0 - Integer $[t/2\pi T_2]\times 2\pi T_2$

$$\omega_2 = \frac{1}{T_2}$$

Parameters A_1, T_1, T_2 are chosen experimentally

$T_2 = 0.5$, sec,

$T_1 = 0.3$, sec,

A_1 was changed in limits (1 - 10 dg).

This signal was developed in [10] as a mean for provoking of PIO phenomena in aircraft-FCS. The example of time process for two configurations demonstrated the described above effect is shown on fig.1.15, 1.16.

The influence of augmentation on equivalent input spectrum

The closure of aircraft coordinate in FCS the deterioration of characteristics of equivalent input spectrum of pilot-vehicle system. This phenomena can be explain with help of the block scheme shown on fig. 1.17a.

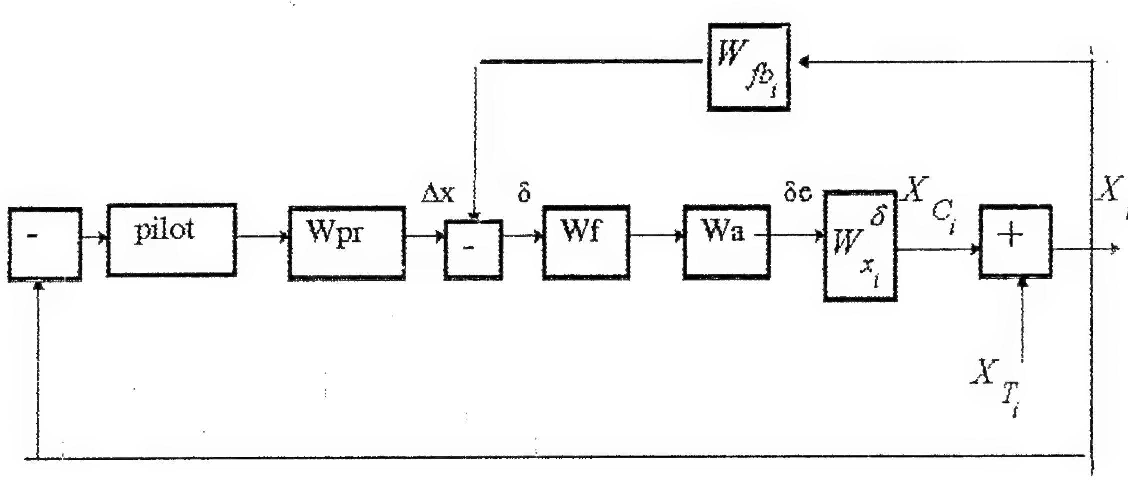


Fig.1.17a

where

X_{c_i} - aircraft output on X_i - coordinate,

X_{T_i} - response of i^{th} coordinate on turbulence input W ($X_{T_i} = W_{c_{x_T}} W$),

$W_{c_{x_T}}$ - transfer function of nonaugmented aircraft.

For pitch angle

$W_c \vartheta_T = \frac{\vartheta_T}{W} = \frac{M_\alpha}{s^2 + 2\xi_{sp}\omega_{sp}s + \omega_{sp}^2}$, where ξ_{sp} and ω_{sp} are defined only by aircraft aerodynamic coefficients,

ΔX - the input for FCS caused by pilot action.

According to this scheme

$$\delta_e = -\sum_i W_{fB_i} X_i + \Delta X$$

Because of

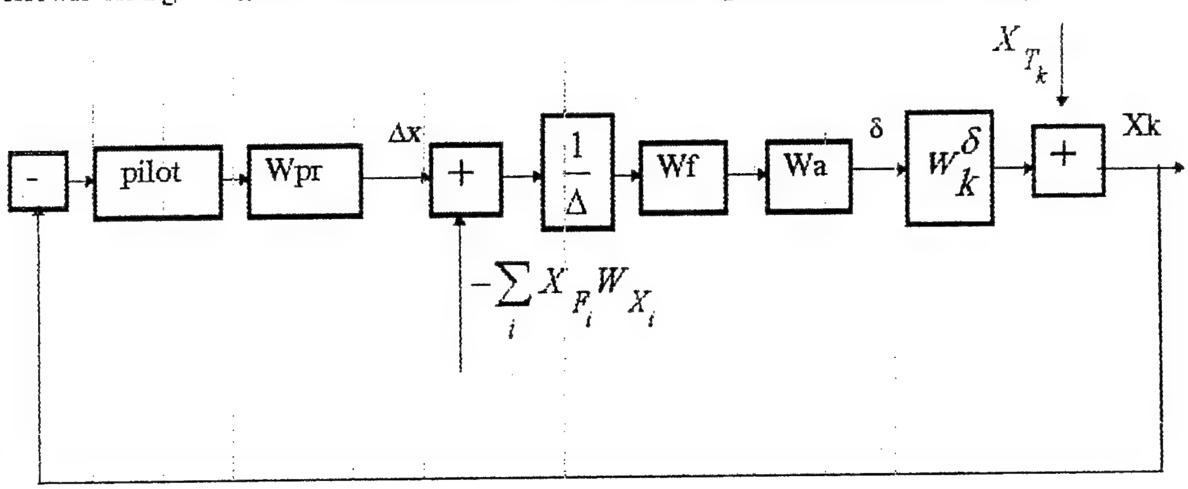
$$X_i = \delta W_a W_{f_i} W_{x_i}^{\delta} + X_{T_i}$$

the equation for δ_e is the following

$$\delta_e = \frac{\sum_{i=1}^{k} X_{T_i} W_{fB_i}}{\Delta} + \frac{\Delta X}{\Delta}$$

where $\Delta = 1 + \sum_{i=1}^{k} W_a W_{f_i} W_{x_i}^{\delta} W_{fB_i}$

Taking into account this equation and supposing the existance of feedback on X_k coordinate, where X_k is the output signal, the pilot-vehicle system, the scheme shown on fig.1.17a can be transformed to one of its equivalent (see fig.1.17б).



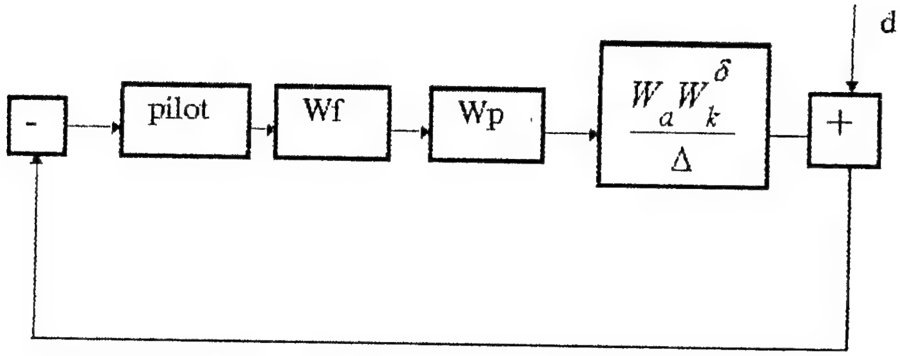


Fig.1.17B

$$\text{where } d = X_{T_k} - \frac{\sum_i X_{T_i} W_{x_i} W_k^{\delta}}{1 + \sum_i W_{x_i}^{\delta} W_{x_i}}.$$

Analysis demonstrates that the spectral density of the signal d has the maximum in the middle frequency range (see the fig.1.17A) and depends on the aircraft dynamics and flight control system parameters. The nearnest of this maximum to the resonance peak, is the reason of increase of the PIO tendency. The experiments fulfilled on simulators with disturbance input confirmed this suggestion. These experiments were carried out for the Drvden model of random lateral velocity $W_y(t)$ demonstrates the obvious maximum in error $S_{ee}(\omega)$, in the middle frequency range. Such sharp maximum is absent for case of target input. Except it the value of variance of error is higher than variance of equivalent input σ_e^2 (fig.1.18B). Preliminary investigations demonstrates the considerable influence of controlled element dynamics on equivalent input signal, d when the inprovement of flying qualities in tacking task accompanied by deterioration of pilot-vehicle system characteristics in case of disturbance input.

1.2.3. The potentialities of current criteria for evaluation of flying qualities of hingly augmented aircraft

Many of well - known criteria were developed in suggestion of conventional dynamics. The appearance of nontraditional dynamics accompaning by considered above specific peculiarities leads to creation of new additional criteria. There are the following:

1. New parameters of aircraft dynamics described the specific peculiarities.

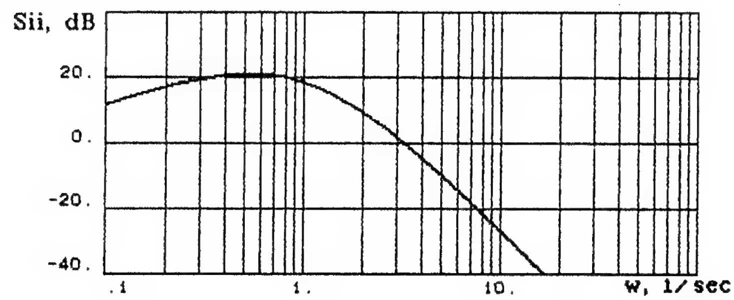


Fig.1.18.a. The spectral density for equivalent disturbance input

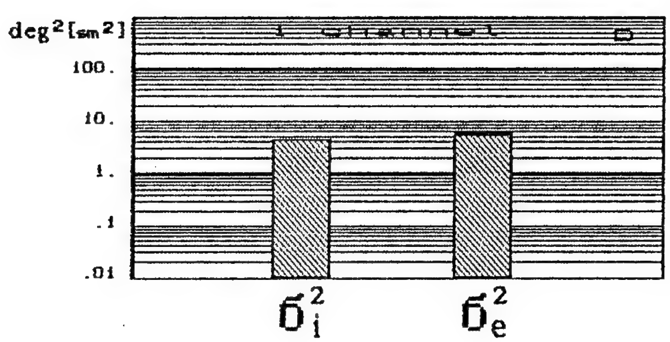


Fig.1.18.b. The variance of error σ_e^2 in case of disturbance input

2. Generalized parameters described the generalyzed characteristics of controlled element dynamics (its decribing function).

3. Parameters determined pilot and pilot-vehicle closed-loop system characteristics.

The necessity in development of new criteria or modification of existed criteria is assosiated with poor agreement between the recommended from standards and experimentally bevaluated flying qualities.

The obvious shortcomings in use of the requirements to parameters of aircraft transfer function as a criteria can be illustrated by different examples. One of them is the discrepency between the well - known boundaries of parameters ω_{sp}, ξ_{sp} recommended in MIL-8785C or STD 1797 for the category A and results of investigation obtained in concrete tracking tasks. There are discussed below the results in investigation of air-to-air tracking task.

With goal to define the possibility to use the well-known requirements to the flying qualities (requirements to ξ_{sp} and ω_{sp}) for evalution of flying qualities in air-to-air tracking task there were carried out the experimental research. There were investigated two controlled element dynamics. One of them corresponded to the aircraft with conventional type of response

$$W_C = K_C \frac{s^2 - Z_W s - \frac{V}{L} Z_W}{s^2 (s^2 + 2\xi_{sp}\omega_{sp} s + \omega_{sp}^2)}$$

The second corresponded to aircraft with ACAH type of response

$$W_C = K_C \frac{(s + 1/T_q)(s^2 - Z_W s - \frac{V}{L} Z_W)}{(s - Z_W) s^2 (s^2 + 2\xi_{sp}\omega_{sp} s + \omega_{sp}^2)} .$$

The parameters were changel and were the following: $-Z_W$ = 1.25, 3.5 1/s, $\omega_q = 1/T_q$ = 1.25, 3.5 1/sec, ξ = 0.286 ÷ 2.0; ω_{sp} = 1 ÷ 1- 1/s. Parameter ω_a was choosen according the equation $\omega_a = 2\xi\omega_q$. For each configuration there were aluated flying qualities according to Cooper-Harper pilot rating scale and were measured the integral, spectral and drequency response characteristics of pilot-vehicle system the distance benween the aircraft and aim was equal 600 m and velocity - 250

m/s. It means that parameter V/L = 0.42 1/s/ It was supposed that the aim moves randomly with the spectral density $S_{ii} = \frac{K_i^2}{(\omega^2 + \omega_i^2)^2}$ where ω_i = 0.5 1/s and variance $\sigma_i^2 = 4$ deg^2 (the variance of projection of the motion is equal to 4 sm^2). For evaluation of flying qualities the desired performance corresponded to the value $d_{des} = 1.75$ sm defined in part 3 for evaluation of aircraft flying qualities in pitch tracking task.

The results of experiments were used for drawing curves of equal PR and equal variances of error σ_e^2, shown on fig.1.19-1.22. Their analysis demonstrates the existance of directions in inprovement of pilot ratings and accuracy (in decrease of variance of error σ_e^2). These directions depend on $-Z_W$ (or n_α) for aircraft with conventional type of response and on parameter of filter $\omega_q = \frac{1}{T_q}$ for aircraft with RCAH type of response. There is seen good accordance between the directions for the first type of aircraft with the line $\omega_{sp} = 2\xi\omega_q$. According to this line the parameters of the second type of aircraft has to be change ($\omega_a = 2\xi\omega_q$).

The obtained requirements to the flying qualities in air-to-air tracking task are shown on fig.1.19-1.22. Their comparoson with the well-known ranges of ω_{sp} and ξ_{sp} demonstrated a poor accordance of requirements.

The next example of poor accordance of recommended and evaluated flying qualities takes place in case of additional filters in flight control system. On fig.1.23 there are shown well - known boundaries of parameters ω_{sp} and ξ_{sp} corresponding to the first and second levels in landing task. In the range of this levels there are given also values ω_{sp} and ξ_{sp} corresponding to a number of LAHOS configurations. In spite of all these configurations have the parameters ω_{sp} and ξ_{sp} belogned to the first level their actual pilot ratings don't correspond to this level.

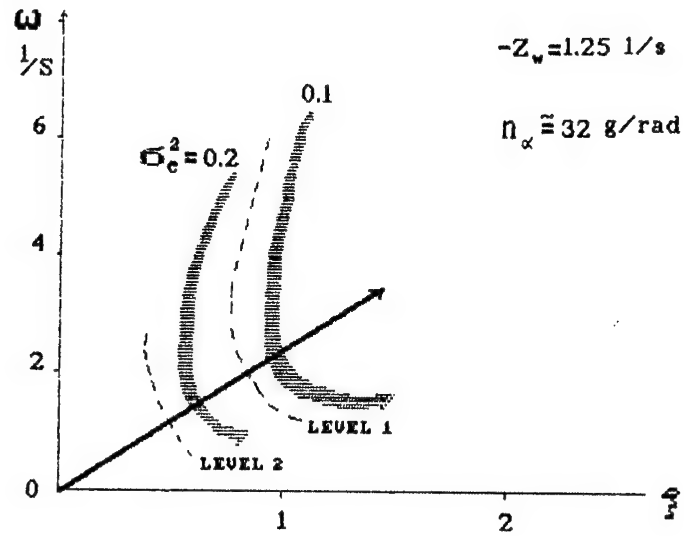


Fig.1.19

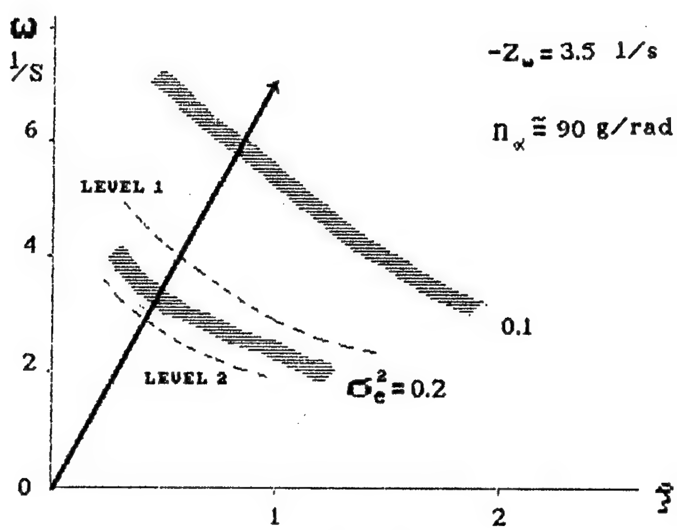


Fig. 1.20.

Lines of equal variances of error and Pilot ratings

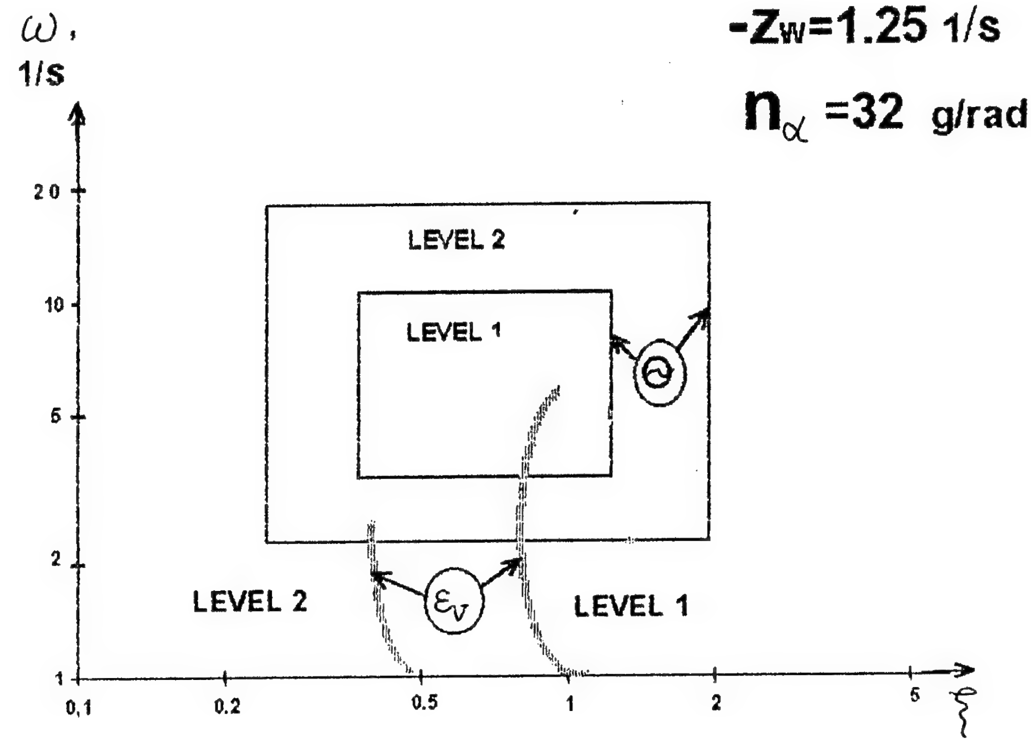


Fig. 1.21

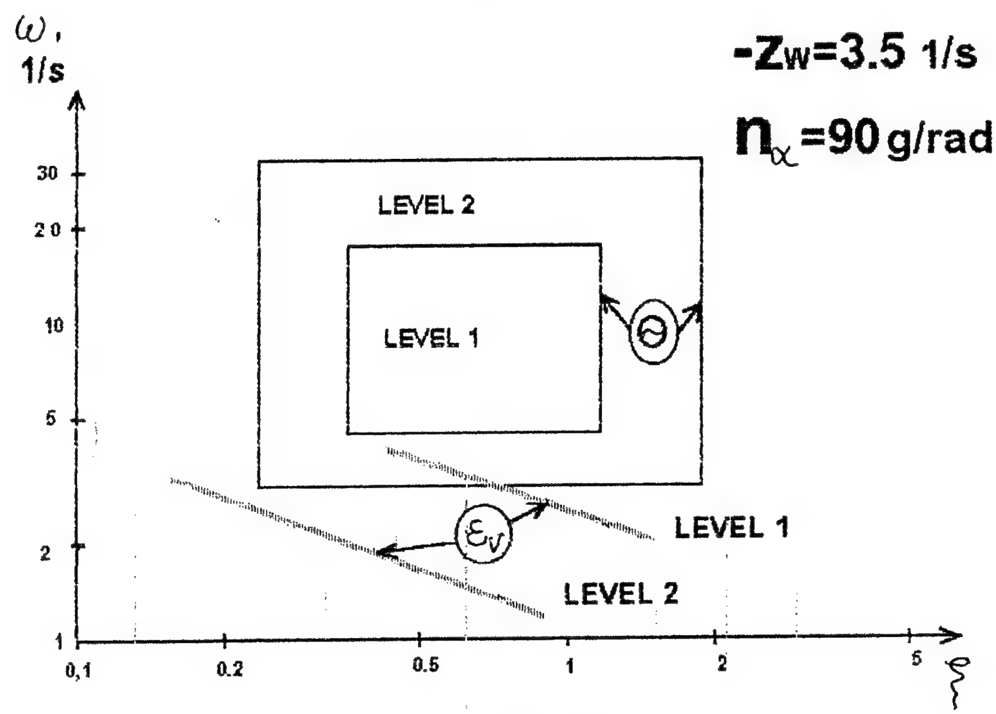


Fig.1.22

Comparison of experimental boundaries of 1 and 2 PR levels in air-to-air tracking task and STD requirements

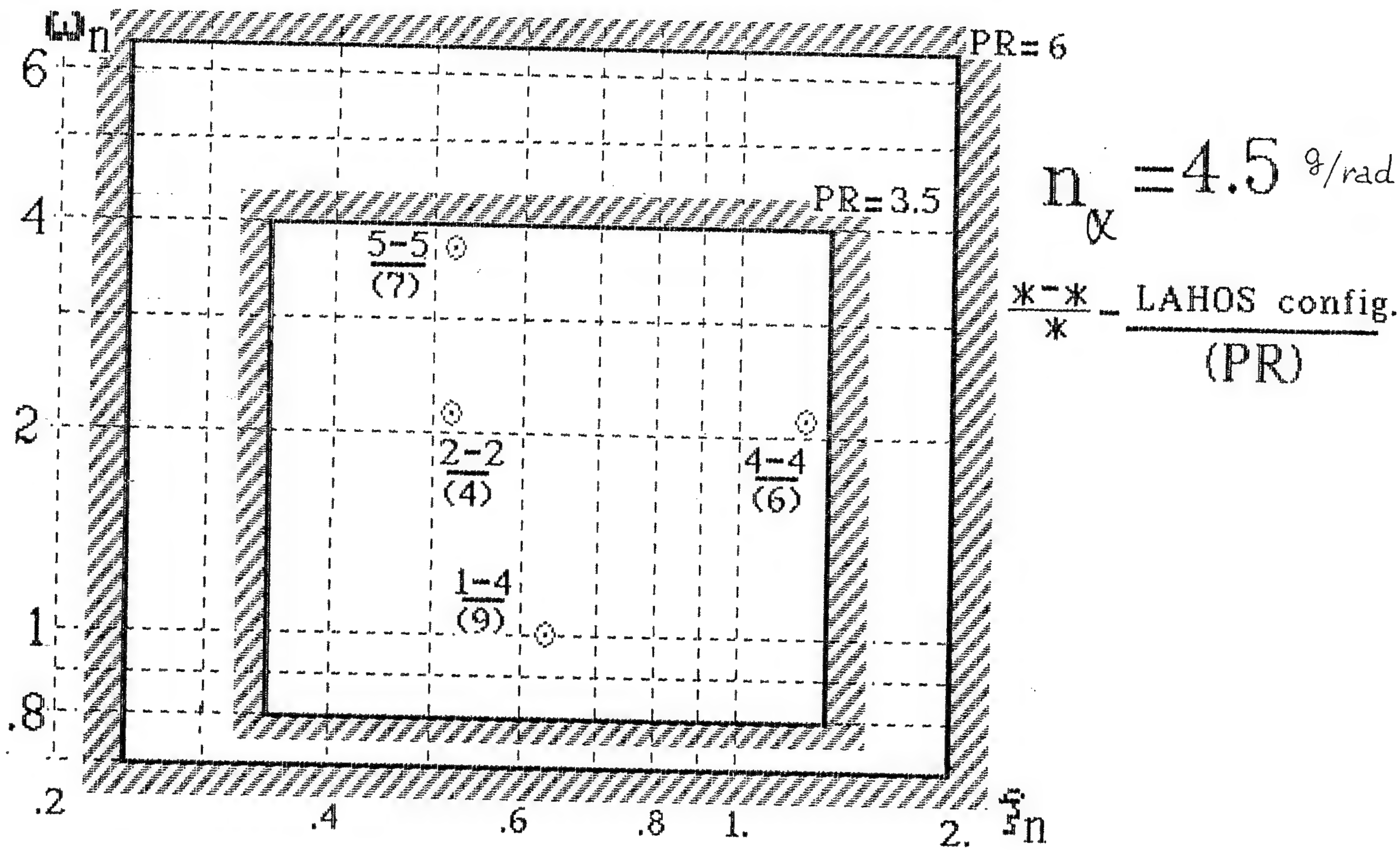


Fig.1.23. The predicted and actual pilot-ratings

Analysis demonstrates that due to the different reasons the new criteria didn't decide the problem in reliable prediction of flying qualities of new generation of aircraft.

One of the new criteria introduced in modern standard is the time delay. Analysis demonstrates that the proposed requirements to this parameters (I level - $\tau \leq 0.1$ s, II level - $\tau < 0.2$ s, III level - $\tau < 0.2\ 5$ s) obtained without taking into account the other characteristics (for example ω_{sp} and ξ_{sp}) don't correspond to actial pilot ratings. For example the aerospace vehicle Buran had the time delay close to $\tau = 0.26$ c. According to the proposed requirements tt is even higher the boundory of the third level at the same time the pilot rating of flying qualities of this vehicle in the landing corresponds to PR $= 4 \div 5$. In [11] there is shown that effect of time delay can be compensated by the corresponding choice of other dynamic characterictics. This task was decided by mathematical modeling where predicted pilot ratings were calculated by the following equuation

$$PR = \alpha_1 \sigma_e^2 + \alpha_2 T_L$$

where $\alpha_1 = 10\ 1/sm^2$, $\alpha_2 = \begin{cases} 3 \ \ for \ \ T_L \leq 0.75 \ \ s \\ 1 \ \ for \ \ T_L > 0.75 \ \ s \end{cases}$, T_L - pilot lead time.

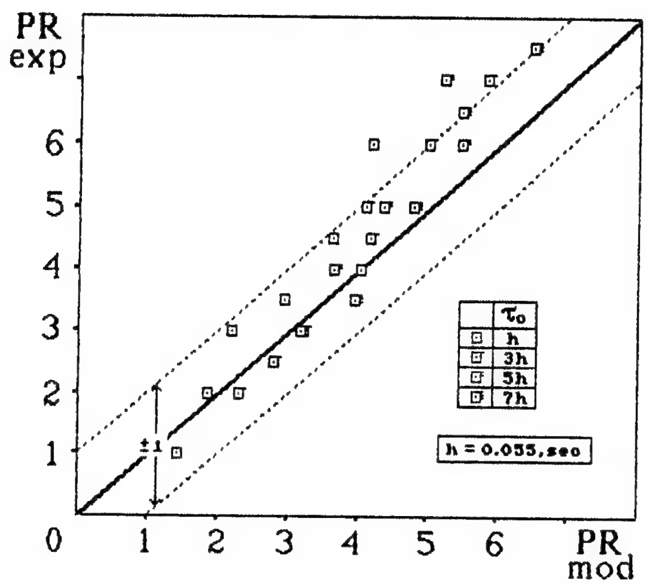
Mathematical modeling of single-loop pilot-vehicle system was carried out by use the the structural approach [14]. Parameters of pilot model were choosen by minimization of variance of error. The results of this modelling are shown on fig.1.24. The lines of equal PR - 3.5 calculoted for the different time delay demonstrate the possibility to keep the satisfactory rating by change the other dynamic characteristics ω_{sp} and ξ_{sp}. In other words the requirements to the time delay and ω_{sp}, ξ_{sp} has to be agreed and has not to be considered seperately. The last takes place in attempts to develop the generalyzed criteria..

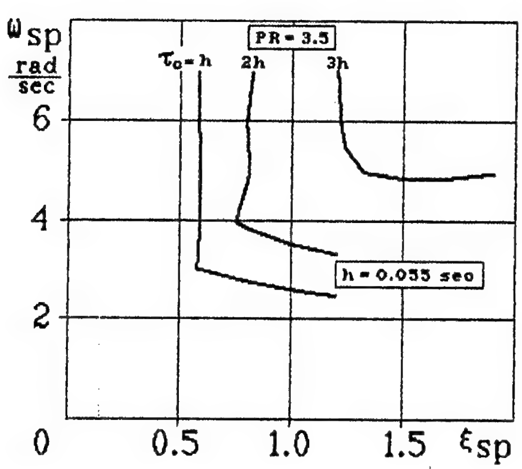
One of such criteria widely used last time is the bandwidth criteria, ω_θ. In many cases this generalyzed criteria allowed to predict the levels of PR rather accurately. However the flying qualities of aircraft characterized by new types of responces (ACAH type) can not be evaluated by this criteria. This limitation can be avoided by use its analog bandwidth of aircraft in path motion, ω_γ. Analysis of different configurations

$$W_c = K_c \frac{(s - Z_w)\, e^{-\tau_c s}}{s\,(s^2 + 2\,\xi_{sp}\,\omega_{sp}\, s + \omega_{sp}^2)}$$

The model for prediction of pilot rating

$$PR = F(\sigma_e^2, T_L) = \alpha_1 \sigma_e^2 + \alpha_2 T_L$$





Example:

$Z_\alpha = 1$ rad/sec
$\omega_{sp} = 2.5$ rad/sec
$\xi_{sp} = 1$
$\tau_p = 0.19$ sec
$$S_{ii} = \frac{K_i}{\omega^2 + 0.5^2}$$

Fig.1.24. The compensation of time delay τ

carried out in [3] demonstrated potentialities of this criteria. The discrepancy with experimental data took place only for configurations with low damping ratio. From path control point of view these configuration have to decrease phase delay and therefore have to supply relately high value of criteria. It has to be accompanied by improvements of pilot ratings. At the same time because of deterioration of flying qualities of these configuration in angular motion the evaluation of flying qualities for these configurations in pith control seighlly deveriorates too. This results demonstrates the problem in correct prediction of flying qualities in path control with taking into account the possible closure the pitch angle in inner loop too.

No one of the mentioned above two types of criteria - parameters of aircraft function or generalyzed parameters didn't take into account the influence of majorily task variables on pilot ratings. The dependence of these variables on results of experimental investigation is one of the main reason of poor accordance between predicted and actual PR.

Such influence doesn't take into account and for the third group of criteria based on standardization of pilot-vehicle system characteristics.

The discussed below one of such criteria Neal-Smith criteria (see fig.1.25) widely used by many investigators. One of its main advantage is potentiality to evaluate flying qualities of aircraft with highly augmented flight control system. Howerer in many research (for example in [12]) it was demonstrated low potentialities of this criteria in reliabe evaluation of flying qualities. The reasons of this shortcoming partly analyzed in [1] are the following.

1. The criteria was obtained as a result of mathematical modelling of pilot-vehicle system for investigated configurations and pilot rating corresponding them. There were not fulfilled no one experimental investigation on identification of standarized parameters of pilot-vehicle system.

The fulfilled in [1] experemental investigations demonstrated the considerable difference with modelling parameters. In table 1.6 there are shown results of such comparison for the several dynamics configuration.

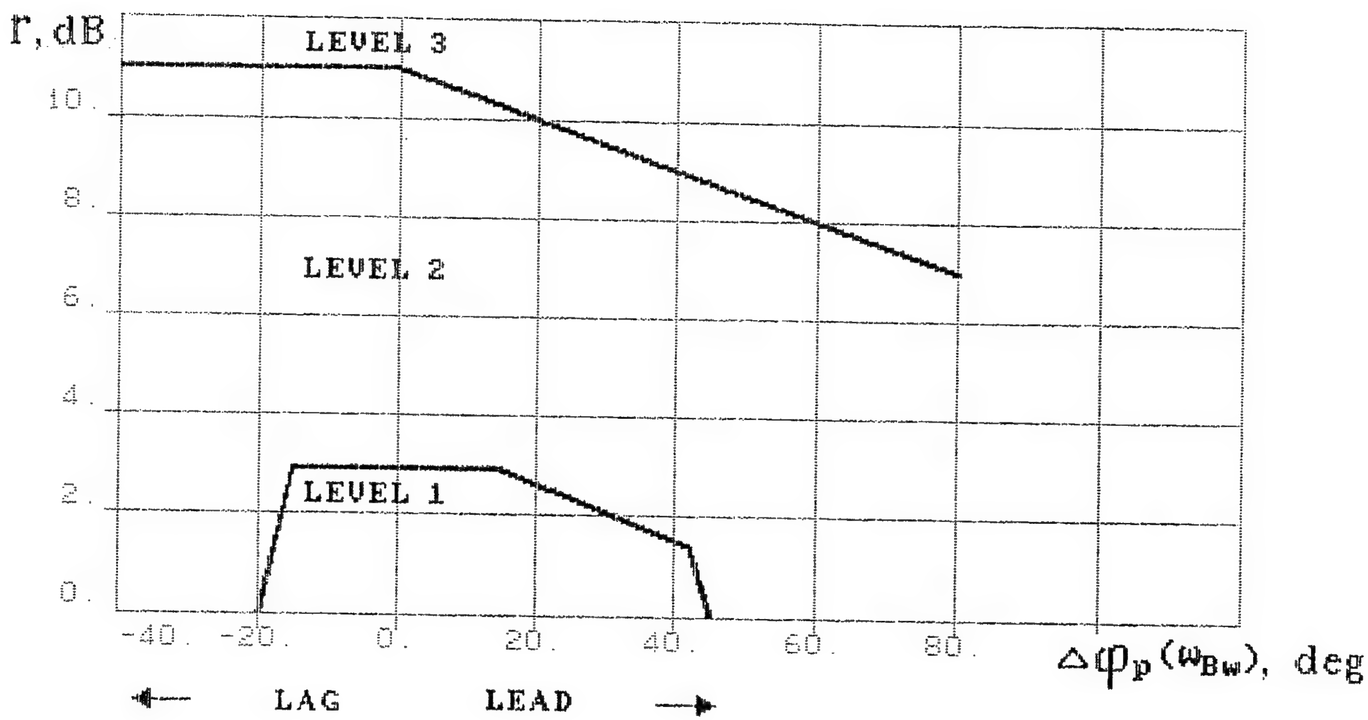


Fig.1.25. Neel-Smith boundaries

Table 1.6

Conf.	5A	2B	1A	2D	2J	2E
r_{exp}	8.7	2.3	7	2	3.8	3.2
r_{mod} $\frac{dB}{dB}$	12	7	4.6	1.4	2.4	1
$\Delta\varphi^{exp}$	-35	-44	+20	-5	+75	+18
$\Delta\varphi^{mod}$ $\frac{deg}{deg}$	-57	-20	+40	-30	+40	+30

2. The poor accordance between the experimental results and modelling used in criteria is assosiated with

- the simpilied models of human behavior (crossover model) used is Neal-Smith procedure. On fig.1.26 there is shown the describing function obtained in experiments with one of the configurations. There is seen that it is considerably more complicated in comparison with chossover model,

- accurate pilot describing function model corresponding to the controlled element dynamics $W_c = K / s$. The procedure used in criteria for calculation of standardized parameters supposes that in case when $W_c = K / p$ pilot behavior has the simplest type and corresponds to $W_p = K_p e^{-s\tau}$. The results of investigation fulfilled in [13] and shown in [1] demonstrated that for case when $W_c = K_c / s$ pilot induces the adaptation in low frequency range increasing for low values of bandwidth and/or sharp input spectrum,

- dependence of bandwidth of pilot-vehicle closed loop system ω_{BW} on the aircraft dynamics. According to the criteria this value is constant for the specific class of aircraft. Variability of bandwidth was exposed in [1] for different configurations covered the 1 class of aircraft. Some results of this research is shown in table 1.7.

Variability of bandwidth

Table 1.7

Configuration	5A	2B	1A	2D	2J	2E
ω_{BW} 1/s	2.9	4.25	3.16	3.4	1.85	3.95

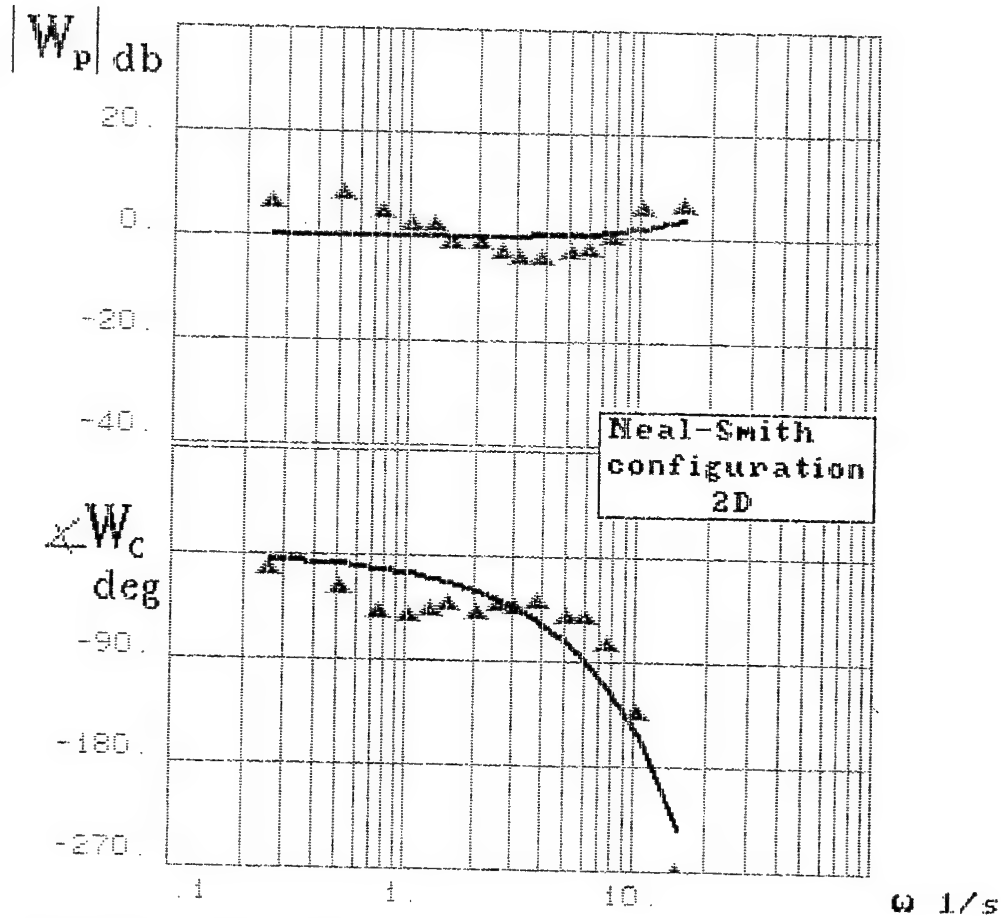


Fig.1.26. Bad egreement between pilot crossover model and experimental Wp(jω)

There is seen that all values ω_{BW} are different and don't correspond to ω_{BW} = 3.5 1/s, which is recommended in STD 1797 for the 1 class of aircraft.

3. The criteria doesn't allow to evaluate any other variable except aircraft dynamics. In [1] there were carefully investigated a number of variables influenced on pilot-vehicle system characteristics considerably. There are the following

- parameters of input spectrum (its form, bandwidth variance),
- permissible level of error.

In spite of considerable influence of these variables on resonanse peal, pilot compensation and pilot rating the criteria doesn't expose any difference in results.

4. The criteria doen't allow to evaluate aircraft flying qualities for any other except, pitch tracking, piloting task.

The criteria was obtained as a result of investigation of pitch tracking task. The attempt to use it for evaluation of flying qualities in other task (for example in landing [13]) were unsuccossfil. The main reasons in descripency in predicted and actual PR re assosiated with the fact that the other piloting task is characterized by complitely different (in comparison with pitch tracking task) set of variables.

All this shortcomings lead to the problem in development of new criteria (or modification of Neal-Smith criteria) allowed to deside all discussed problems. Partly this task was decided in [1]. In current report this task has the further continuation.

The closure of pilot-vehicle system can cause the pilot induced oscillations (PIO). Because of discussed above dynamic peculiarities PIO tendency is character for the highly augmented aircraft. In spite of this phenomena is well-known and decreases the flight safety considerably there is no relibale criteria for its prediction up to now. The research in this area was carefully investigated in [1]. The current work is continuation of this too.

1.3. The main tasks in development of standardization of flying qualities and approach for their solution

Due to the main part of flying qualities of aircraft and its PIO tendency are exposed themself basically when a pilot closes the loop the development of criteria for their prediction has to be decided by consideration of pilot-vehicle closed-loop system. The obligatory requirement in development of criteria is the high level of reliability in prediction. For this purpose in Moscow Aviation Institute it was developed the system

approach which is unique for the other manual control tasks (flight control system design, development of piloting technique, etc) too. The main principles of this approach are shown on fig.1.27. The context of the approach can be formulated by the following way:

- the solution of each applied manual control task has to be carried out by consideration of plurality piloting tasks such as air-to-aur tracking, terrain following, refueling, etc,

- for each piloting task, it has to be chosen the variables adequated to the considered task. These variables are devided on two groups: task variables (controlled element dynamics, interfaces, input signal) and pilot's variables. The detail analysis of this variables and their dependence on piloting task is given in [1],

- the solution of any applied manual control task has to be carried out by investigation of pilot-vehicle closed loop system adequated to the considered piloting task. It means that it has to be defined the loops closed by pilot, the type of the system (stationary, unstationary),

- the core of the system are the methods for experimental investigation and mathematical modelling. The main requirements to the methods are the accuracy in measurements and prediction of results. These methods were developed in MAI and are given in [1],

- the subject for the study are the pilot control and psycophysulogical response characteristics. In [1] there were defined these groups of characteristics and algorimths for their measurements,

- in process of study of these characteristics there are exposed the regulary in pilot behavior which are the basis for the solution of investigated tasks.

The wide use of this approach allowed to expose a number of fundamental regularities in pilot behavior:

- low frequency pilot's adaptation,

- pilots ability to induce the adaptation in all frequency ranges,

- the active use of additional kinestatic information in case when controlled element dynamics has increased time delay,

- the difference in perception of motion cues in experiments with target or disturbance inputs,

- considerable influence of permissible level of error and dependence of many other variables on pilot behavior.

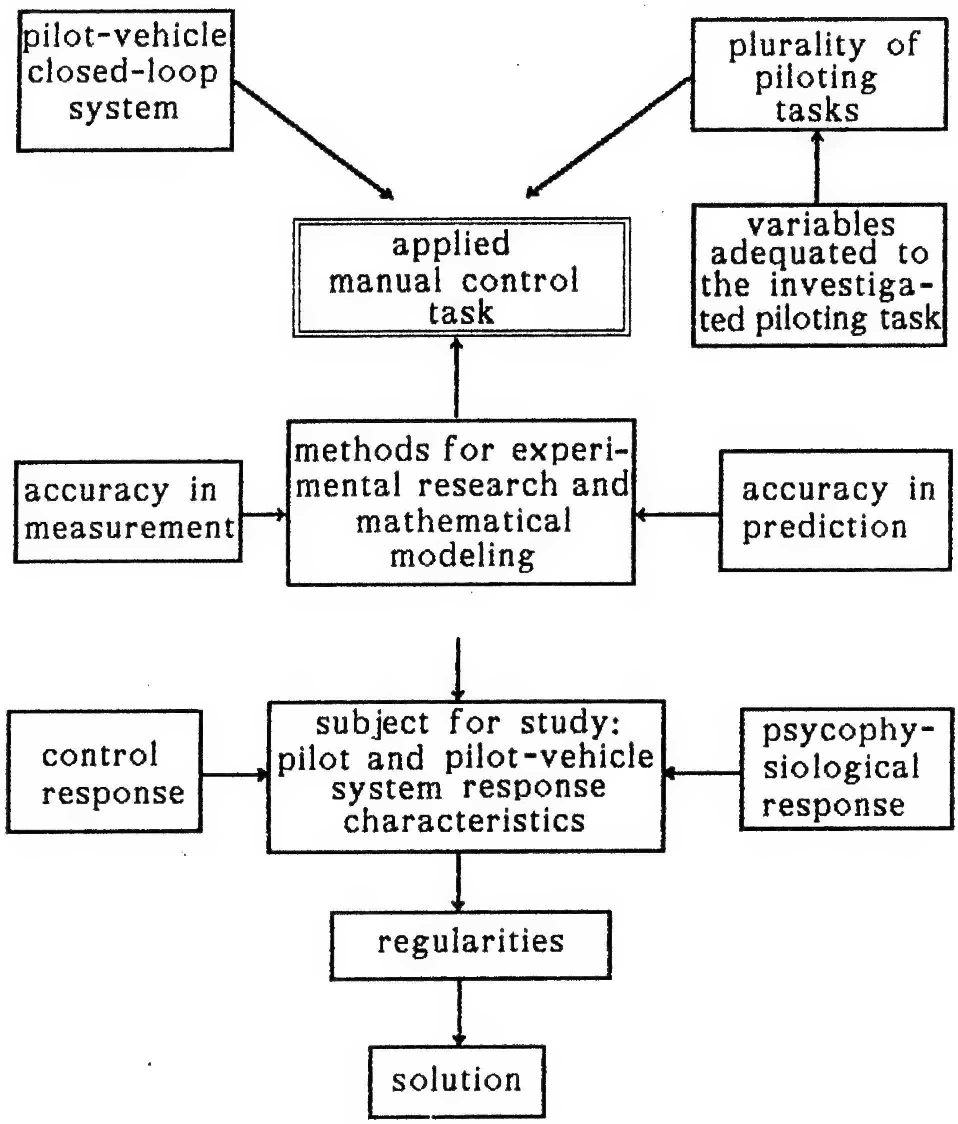


Fig.1.27. System approach to the manual control tasks

These and many other regularities (see [14]) exposed with help of system approach were widely used for solution of applied manual control tasks. With their help it was determined the optimal control element dynamics [9,14], are defined the algorithms for simulation of motion cues [14], was created the new type of manupulator with dynamically changeble spring striffness [15], was developed the criteria for the prediction of PIO tendency [1], were obtained many other results.

The further work on development of criteria for the prediction of flying qualition by use the system approach requires:

- to define the ways of taking into account the factor of plurality of piloting tasks,
- to determine the additional variables for their further standardization,
- to expose the system parameters (parameters characterized pilot-vehicle system) for the furter standardization,
- to define the key parameters of Cooper Harper scale (task performances and pilot compensation) in each piloting task.

In case if the criteria developed from pilot-vehicle system consideration will be included in new version of standards the problem of their verification on different stages of aircraft design will be arizen.

For purpose of such verifications it has to be developed the corresponding means uncluding methods, facilities and software. The study of this problem is out of the frame of the report.

CHAPTER 2

EVALUATION OF FLYING QUALITIES IN PRECISE PILOTING TRACKING TASKS

2.1. General conception

The evaluation of flying qualities in precise tracking tasks is evaluation of accuracy and pilot compensation of negative aircraft dynamic characteristics necessary for its achievment.

The characteristics of accuracy and pilot compensation define so-called "The flying qualities parameter" J. The interval of this parameter lies in limits from J_{opt} (for case when aircraft has optimal dynamics, $W_C^{opt}(s)$) up to J_{input} (for case when $W_C = \overset{*}{W_C}(s)$). For aircraft with transfer function $\overset{*}{W_C}(s)$ any pilot's attempt to close the pilot-aircraft system and to work accuratly causes only a deterioration in accuracy. The analysis of piloting tasks carried out in chapter 1 and in [1] too demonstrates the considerable difference in aircraft dynamics and input signals in each of them.

There is considered below a case when the spectral density of input signal has the same form and different variances for the different piloting tasks. That is absolutely correct for angle of sight control, for the different distance L between aircraft and aim. In chapter 1 it is shown in detail that for high distance L the output in pilot-vehicle system is pitch angle, for intermidale L the output is $\varepsilon_L = \vartheta + H_p / \overset{*}{l}$, and for relatevely small distanse - ΔH. For all these distances the input spectal density is the same but the variance σ_I^2 are different. For high and intermidiate distances $\sigma_I^2 = f(\frac{1}{L^2})$ all these piloting tasks are the tasks of the same class - singleloop compensatory task. The correlation between pilot rating and Flying Qualities Parameter (FQP) can be obtained for all of them by evaluation of pilot-vehicle system potentialities on decrease of error and pilot compensation. For this purpose there is quite enough to combine all known dynamic configurations (from all piloting task) in unique data base and to carry out the evaluation their flying qualities in the same conditions.

There is necessary to notice that due to considerable difference of aircraft dynamic characteristics in different piloting tasks and impossibility to compensate this factor equally with help of pilot compensation. The different minimum values of FQP $J_{\min}^{task}$ and pilot rating $R_{\min}^{task}$ can be reached in each piloting task. This conclusion is shown on fig.2.1 for the relative FQP $\bar{J} = J / J_{input}$. The parameter J_{input} is defined by variance of input signal.

The results of this analysis demonstrate that there is possible a case, when in concrete piloting task the best flying qualities can be outside the first level of pilot rating (see fig.2.1 tasks 2,3). On the other side there is Flying Qualities parameter J_{des}^{task} for each piloting task which value is defined by the first level boundary of flying qualities. For example in refueling task J_{des}^{task} is defined by the size close to the size of central holl of droque. The hit in this size supplies the fulfilment of refueling task with high probability. Thus the problem in agreement of conditions for evaluation with value of J_{des}^{task} is arizen. There is necessary to define the value of input signal to supply the fulfilment of the following condition $\bar{J}_{des}^{task} > \bar{J}_{\min}^{task}$.

After the agreement of all conditions there is possible to get the function $PR = F_{task}(\bar{J})$ from the general function $PR = F(\bar{J})$ by its displacement down up to its crossing with the point ($\bar{J}^{task}$, PR_{Level1}). This procedure is shown on fig.2.2.

Thus the procedure on evaluation of flying qualities of different piloting tasks consists of the following stages.

<u>At the first stage</u> it has be evaluated the dynamic configurations for all piloting tasks represented by the same structure of pilot vehicle system, including the configuration with optimal dynamics. As a result there is defined the common for all configurations function PR = F($\bar{J}$).

<u>At the second stage</u> the conditions for evaluation (variance of input signal) is agreeded with requirement on fulfilment of the piloting task J_{des}^{task}. For this task there is defined its own function $PR = F_{task}(\bar{J})$. It allows to determine the corresponding to

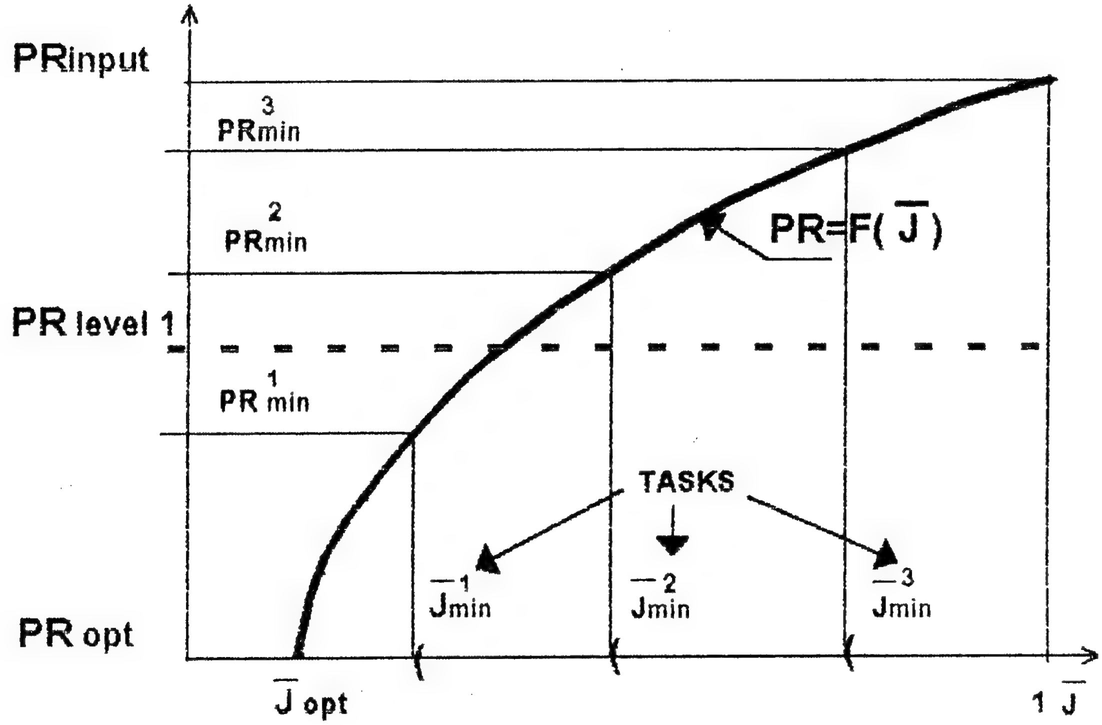


Fig.2.1 The general function PR=F($\bar{J}$)

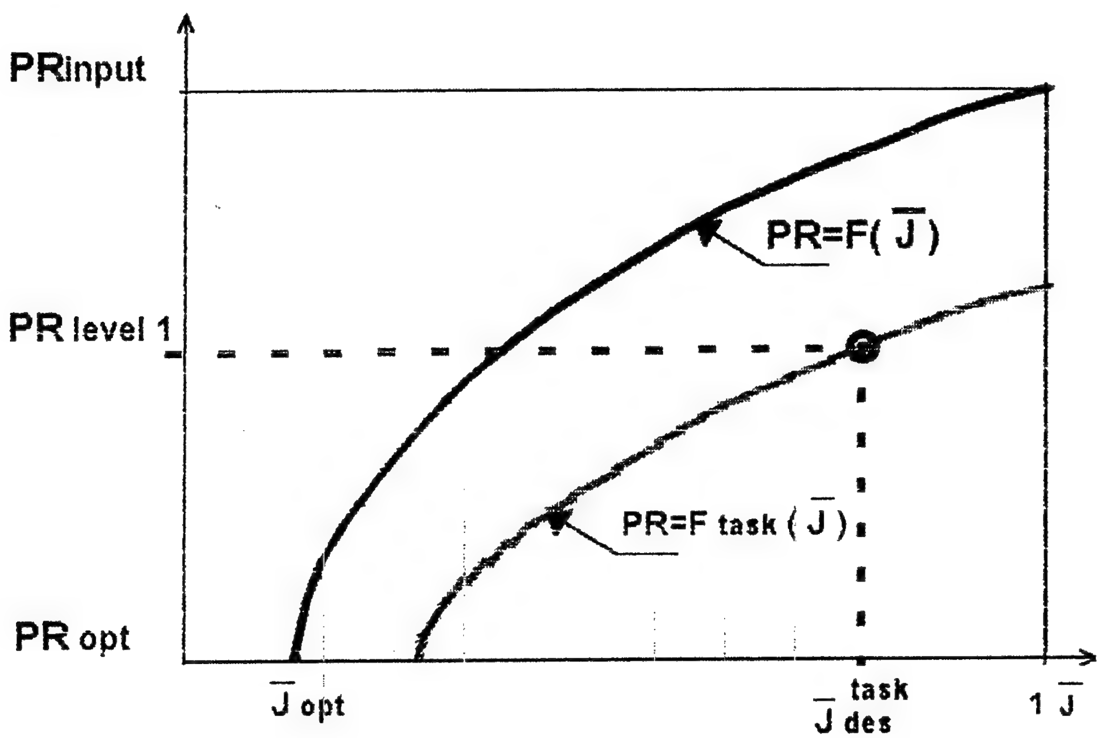


Fig.2.2 The function PR=Ftask($\bar{J}$)

the investigated piloting task the desired and adequate performances for evaluation of flying qualities in concrete piloting task.

The discussed procedure was used in chapter 3 for evaluation pf flying qualities in refueling task.

2.2. Development of technique for evaluation of flying qualities by use the piloting ratings

The pilot rating is a widely used and more general flying qualities criteria. It can be considered as an integral generalization of all his perceptions about the aircraft motions in fulfilment of mission (or piloting task) expressed in corresponding units. For quantitive expression of the results of this process there are used the pilot subjective rating scales.

The improvement of procedure for evaluation of flying qualities, determination of relation between pilot rating and flying qualities parameter requires the careful analysis of Cooper-Harper scale (fig.2.3). Analysis shows that there are two qualitively different interval of ratings. Up to PR = 7 the ratings define the potentialities in achievement of one from three values of task performance (for compencatory task "the task performance" is the parameter of accuracy) desired (PR = 1 ÷ 4) adequate (PR = 5 ÷ 6) and more then adequate (PR = 7). The further deterioretion of pilot ratings (PR = 8, 9, 10) is just assosiated with the possibility to carry out manual control. The second "the key parameter" of Cooper-Harper scale (see fig.2.3) is a pilot compensation. The difference in level of pilot compensation is accompanied by difference in pilot rating on one unit.

The levels of pilot compensation have the following categories: abscence of compensation, minimal, moderate, considerable, extensive, maximum tolerable. There are two remarks below based on the knowlege of pilot-vehicle system characteristics regularities [1,14]:

- All mentioned above categories of pilot compensation correspond a parameter of the complexity of adaptation induced by pilot to supply optimal characteristics of closed-loop system. For example the absense of compensation corresponds to a case when pilot is not required to induce any additional compensation to proportional type of behavior. The other category of compensation corresponds to pilot adaptation activity with the definited level of complixity.

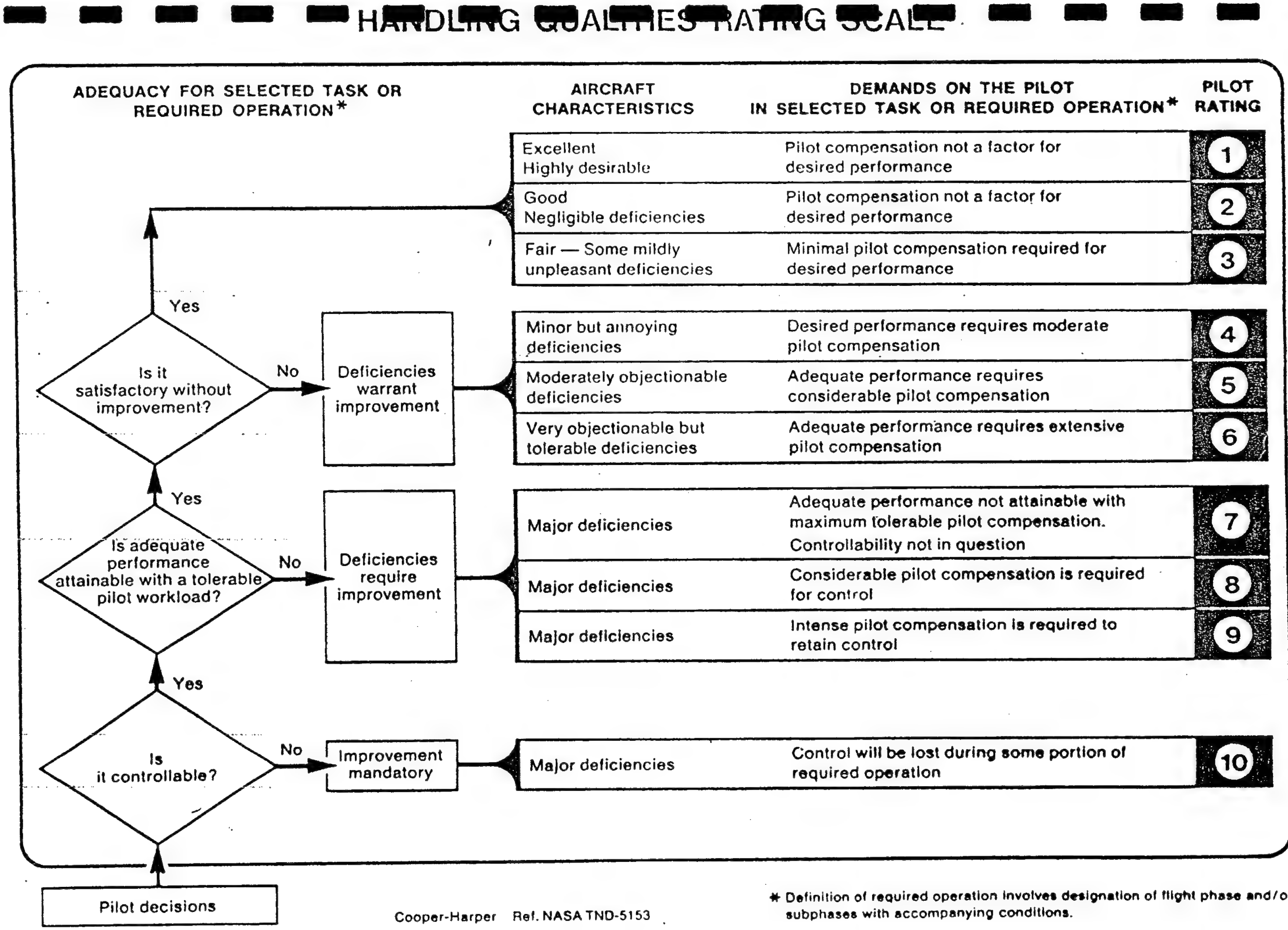


Fig.2.3. Cooper-Harper rating scale

- For each piloting task there is possible to determine the optimal dynamic configuration for which pilot behavior will correspond to the proportional type. Algorithm for the definition of such configuration is given in [14].

There is obviously that such controlled element dynamics will and have to be evaluated with $PR_{opt} = 1$.

It will supply also the highest accuracy in fulfilment of the piloting task.

If we shall define the accuracy as a featur of current error e(t) to be inside the specific interval d then for the optimal dynamic configuration this interval d_{opt} will be a minimum.

The deterioretion of aircraft flying qualities causes pilot to induce the corresponding compensation (lead or/and lag), what doesn't allow him to realyze the same optimal characteristics of pilot-vehicle system as for optimal configuration. As a consequence the accuracy in fulfilment of piloting task will deteriorete too. The current error will be outside the interval d_{opt} more frequently basically. It will be in the interval d = d_{opt}+Δd. The value Δd characterized the deterioretion of accuracy will increase when the flying qualities will deteriorate. It will be accompanied and by increase of necessary pilot compensation too.

This value Δd can be considered as an integral parameter of compensation. It defines the cost for deterioretion in accuracy due to necessity to induce pilot compensation to suppress the negative flying qualities.

From all these considerations the conclusion can be made that there is quite definite relation between pilot ratings and parameter of accuracy colled Flying Qualities Parameter (FQP) reflected the description of Cooper-Harper key parameter.

For precise manual control tasks FQP is a value of interval d for which the current error e(t) will be inside with very high probability.

The definition of concrete equation of such relation PR = F(d) = F(d_{opt},Δd) is the part of the technique for evaluation of flying qualities. Its knowledge allows to choose the parameters of the desired and adequate task performance and integral parameter of pilot compensation.

2.3. The relation between pilot-rating and Flying qualities parameter

In many investigation there is used wellknow psycophysiological Weber-Fechner law [1]:

$$PR = A \ln J + B \tag{2.1}$$

where the constants A and B defined by regressive analysis of experiments of many dynamic configurations. The results of these experiments consist of pilot ratings PR and flying qualities parameter. There is offered the following analytical procedure for definition of parameters A and B. There is supposed that for aircraft optimal dynamics PR = 1 and J = J_{opt} and for aircraft with dynamics corresponding to PR = 4 the flying qualities parameter J = J_{des}. For these configurations (2.1) corresponds to the following two equations

$$\begin{Bmatrix} 4 = A \ln J_{des} + B \\ 1 = A \ln J_{opt} + B \end{Bmatrix} \tag{2.2}$$

The constants A and B are defined by the equations

$$A = \frac{3}{\ln \frac{J_{des}}{J_{opt}}}$$

$$B = 1 - 3 \ln J_{opt} / \ln \frac{J_{des}}{J_{opt}}$$

Taking it into account the equation (2.1) can be rewriten as

$$PR = 1 + \frac{3}{\ln \frac{J_{des}}{J_{opt}}} \ln \frac{J}{J_{opt}} \tag{2.3}$$

or

$$PR = 1 + \frac{3}{\ln \frac{J_{des}}{J_{opt}}} \ln(1 + \frac{\Delta J}{J_{opt}}) \tag{2.4}$$

where $\Delta J = J - J_{opt}$ is the integral parameter of pilot compensation or the cost for increase of Flying Qualities Parameter J caused by the necessity to induce pilot compensation to suppress the negative aircraft flying qualities. For precise tracking tasks the permissible level of error d can be considered as a parameter J. It reflect the task performance and pilot compensation.

It that case equation (2.4) can be rewriten

$$PR = 1 + \frac{3}{\ln \frac{d_{des}}{d_{opt}}} \ln(1 + \frac{\Delta d}{d_{opt}}) \qquad (2.5)$$

where $\Delta d = d - d_{opt}$ is equivalent to ΔJ.

2.4. Adequancy of conditions for evaluation of flying qualities

In evaluation of flying qualities fulfilled for the different spectral densities of input signal there is necessary to have the adequate conditions for evaluation.

There is supposed below that conditions 1 and 2 are adequate if the pilot ratings of the same dynamic configuration are equal for them. By use (2.5) there is possible to get the following equation

$$\left.\frac{\ln(1 + \frac{\Delta d}{d_{opt}})}{\ln \frac{d_{des}}{d_{opt}}}\right]_1 = \left.\frac{\ln(1 + \frac{\Delta d}{d_{opt}})}{\ln \frac{d_{des}}{d_{opt}}}\right]_2$$

This equation will be correct when

$$\left.(1 + \frac{\Delta d}{d_{opt}})^k\right]_1 = \left.(1 + \frac{\Delta d}{d_{opt}})\right]_2$$

$$\left.(1 + \frac{d_{des}}{d_{opt}})^k\right]_1 = \left.(1 + \frac{d_{des}}{d_{opt}})\right]_2 \qquad (2.6)$$

The order k in general case can have any value. For case when $k = 1$, (2.6) transforms in the following equation

$$\left.\frac{\Delta d}{d_{opt}}\right]_1 = \left.\frac{\Delta d}{d_{opt}}\right]_2 \qquad (2.7)$$

$$\left.\frac{d_{des}}{d_{opt}}\right]_1 = \left.\frac{d_{des}}{d_{opt}}\right]_2 \qquad (2.8)$$

Taking into account that $\Delta d = d_{ad} - d_{opt}$ the equation (2.7) have following form:

$$\left.\frac{d_{ad}}{d_{opt}}\right]_1 = \left.\frac{d_{ad}}{d_{opt}}\right]_2 \qquad (2.9)$$

And finally from (2.8) and (2.9) there is easy to get

$$\left.\frac{d_{ad}}{d_{des}}\right]_1 = \left.\frac{d_{ad}}{d_{des}}\right]_2$$

Thus the Cooper-Harper pilot ratings PR for the same configuration will be same for conditions 1 and 2 in case if its relative scale will be $\Delta d / d_{opt}$.

Thus, the ratios $\Delta d / d_{opt}$, d_{des} / d_{opt}, d_a / d_{opt} and d_{ad}/d_{des} are the constants (for case k = 1) in the task of evaluation flying qualities. The fulfilled above analysis demonstrates that the determination of these constants can be carried out by fulfilment of experiments with one data base, for example with Neal-Smith data base given in [16] . In investigation of other piloting tasks and/or other conditions for their modelling there is necessary to determine the value d_{opt} first of all. Then the knowledge of constants allows to define the values d_{des} and d_{ad} corresponding to the new conditions. Only after this stage there is possible to decide the task of flying qualities evaluation in new conditions.

2.5. The determination of the constants and test of the function PR = f(J)

The data base given in [16] contians: the description and values of parameters of dynamic configurations in pitch angle control tracking task and Cooper-Harper pilot ratings in wide range of PR (PR = 2.5 ÷ (7 - 8)). In current research it was evaluated the values of d_{opt}, d_{des}, d_{ad} with help of workstation and method of experimental investigations considered in [1].

The order of the research was the following. For conditions corresponding to Neal-Smitch data base ($S_{ii} = \dfrac{K}{(\omega^2 + 0.5^2)^2}$; σ_i^2 = 4 sm² see [1]) and taking into account typical pilot's limitation parameters (time delay, remnant) there were calculated the optimal controlled element dynamics $W_{c_{opt}}$ with help of workstation then there were carried out the experiments on workstation with goal to define interval d_{opt} corresponding to $W_{c_{opt}}$. In the same way but for Neal-Smith configurations corresponding to PR = 4 and PR = 6 there are carried out the experiments to determine the "value" of Flying Qualities Parameters d_{des} and d_{ad}.

The experiments gave the following values d_{opt} = 1 sm, d_{des} = 1.75 sm, d_{ad} = 2.54 sm defined the corresponding constants

$$\frac{d_{des}}{d_{opt}} = 1.75; \ \frac{d_{ad}}{d_{des}} = 1.45.$$

These values allowed to define the following equation for the function PR = f(J)

$$PR = 1 + 5.361 \ln\left[1 + \frac{\Delta d}{d_{opt}}\right] \tag{2.10}$$

2.4 This function is shown on fig.2.4. With purpose of the test of this equation it was carried out a series of experiments on workstations where the operators determined the value of Flying qualities parameter d by fulfiment of experiments. The results of these tests shown on fig.2.4 demonstrated good agreement with the equation (2.10). The results of comparison of these equation with results of experiments fulfiled for HAVE PIO configurations shown on fig.2.5 demonstrated good agreement too.

All these results allowed to recommend the developed equation and technique for evaluation of handling qualities in different singleloop precise tracking task.

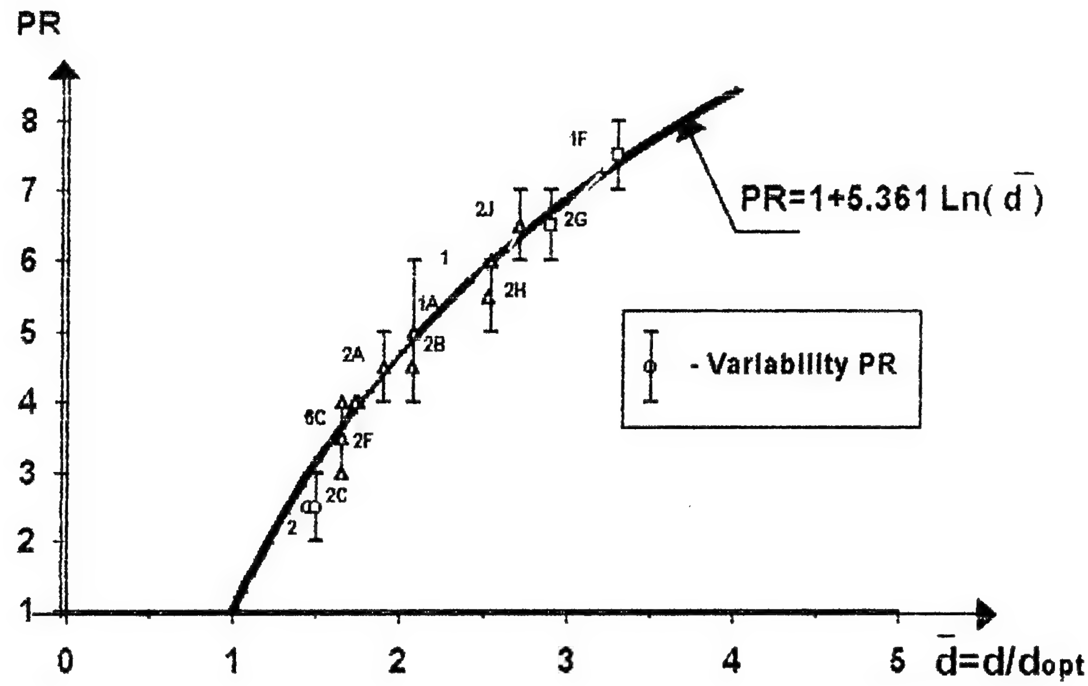


Fig.2.4. Agreement of the fanction PR=F(J) with experiments for Neal-Smith configuration

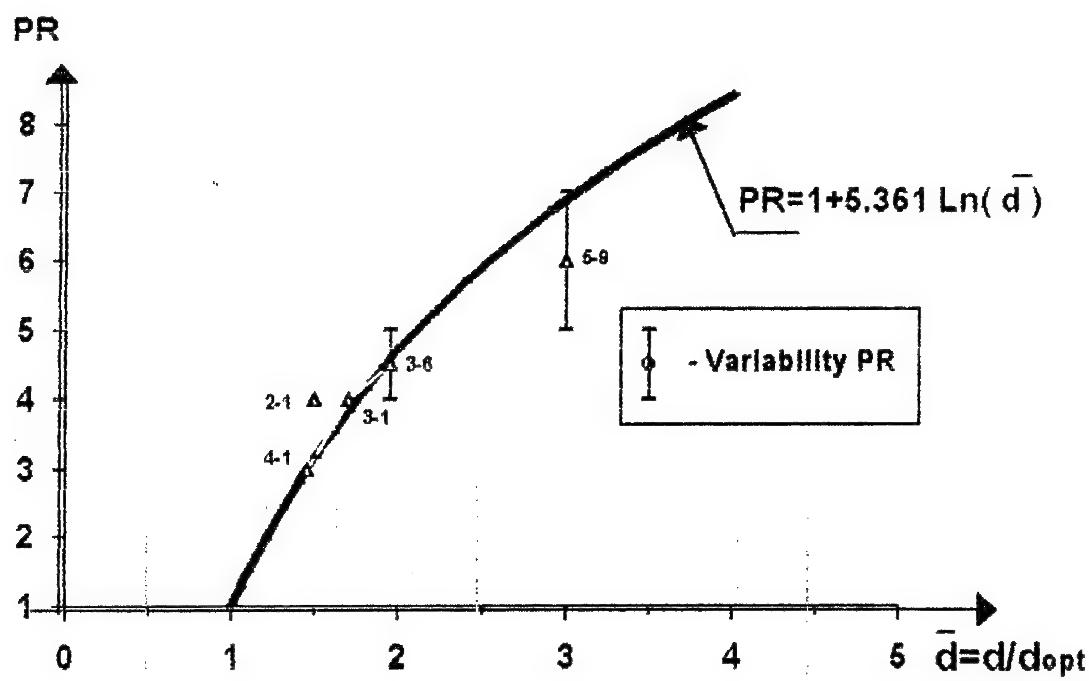


Fig.2.5. Agreement of the fanction PR=F(J) with experiments for HAVE-PIO configuration

CHAPTER 3

THE DEVELOPMENT OF CRITERIA FOR EVALUATION OF FLYING QUALITIES BASED ON STANDARDIZATION OF PILOT-VEHICLE SYSTEM CHARACTERISTICS

Taking into account the considerable influence of piloting task on characteristics of pilot-vehicle system it was carried out the research in development of criteria for evaluation of flying qualities in two different piloting tasks. One of them is the angular control when output of controlled element dynamics is angle of sight, $\varepsilon \cong \theta + \frac{\Delta H}{L}$. In case of considerable distance (L) between the pilot and aim this task is the pitch control tacking task. The other investigated task is the refueling task. At the last stage of its fulfilment it is practically altitude tracking task when the controlled element output is $\varepsilon L \cong \theta L + \Delta H \approx \Delta H$. The work on development of criteria for prediction of flying qualities in pitch tracking task is the continuation of research carried out in [1].

3.1. Accordance of Have PIO configurations to the Moscow aviation institute criteria

In [1] there were carried out the careful experiments for Neal-Smitch and LAHOS configurations.As a results of this research, it was obtained the criteria for the prediction of PIO tendency and aircraft flying qualities "MAI criteria" (see fig.3.1). In current research it was fulfilled experiments to for the allowed to measure the closed loop system resonanse peak, r, and pilot compensation parameter W for 18 Have PIO configurations [2], given in table 3.1. The measurements were fulfilled according to technique considered in [1]. The comparison of results with criterias bounderies demonstrates the good agreement with levels of pilot ratigs drawn in range φ, W. On fig.3.1 there are given results of experiments with 66 investigated configurations (Neal-Smitch (23), LAHOS (25), Have PIO (16)). The corresponding data for all these configurations are given in table 3.2, 3.3, 3.4.

In parallel with evaluation of flying qualities on Cooper-Harper scale it was used PIO rating scale too. The comparison of PR and PIO ratings for HAVE PIO configurations shown on fig.3.2, demonstrated good accordance between these ratings. These results confirm the high potentialities of MAI criteria developed in [1].

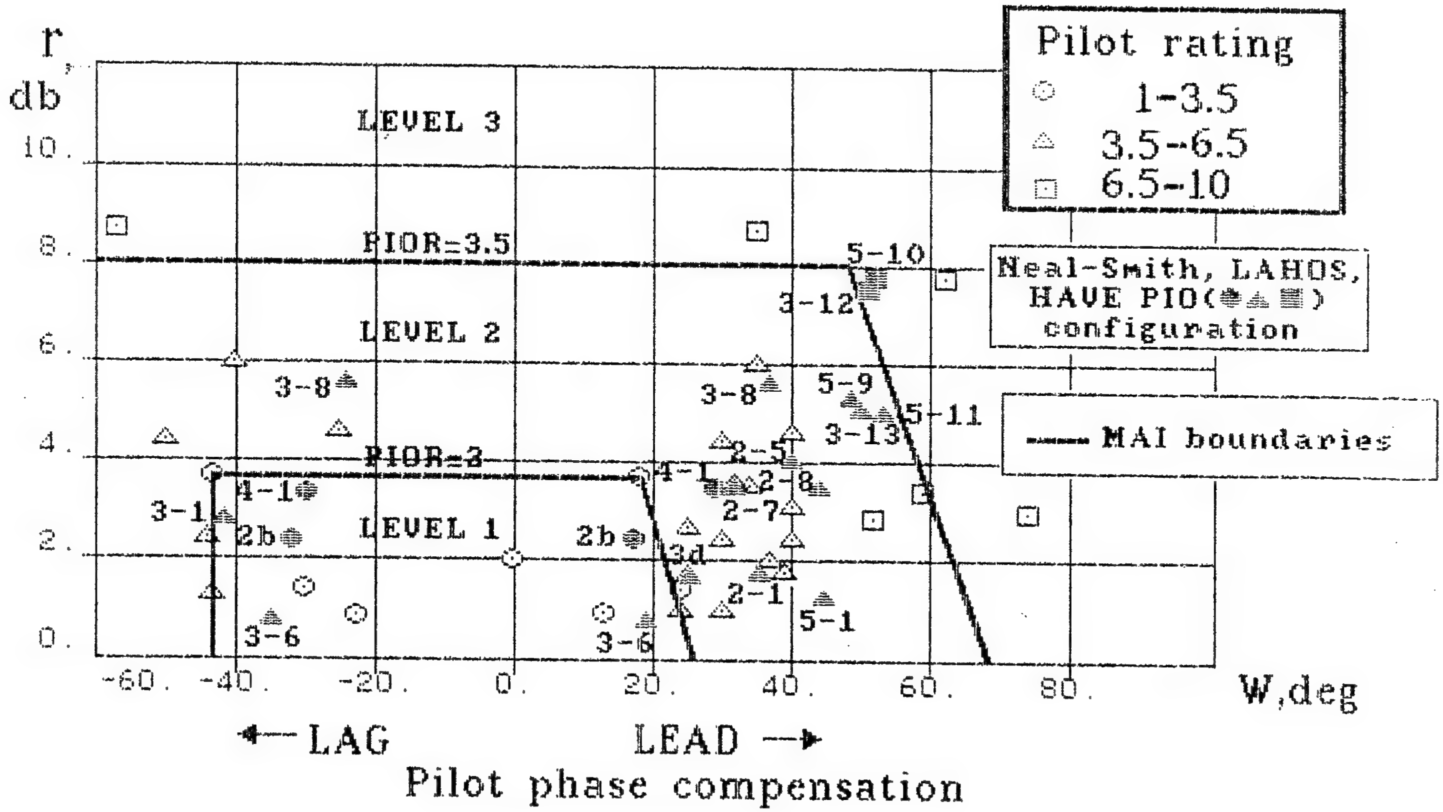


Fig.3.1. The correlation of closed loop parameters with developed criteria

$\tau_{\theta_2} = 1.4$ s

Configuration	$1/\tau_1$	ω_{n_1}/ξ_1	$1/\tau_2$	ω_{sp}/ξ_{sp}	ω_{n_2}/ξ_2	Pilot rating
2-B	3.33	–	10.	2.4/0.64	–	7/3/3/3
2-1	∞	–	∞	2.4/0.64	–	2/2/3
2-5	∞	–	1.0	2.4/0.64	–	10/7/10
2-7	∞	12/07	∞	2.4/0.64	–	7/4/4
2-8	∞	9/07	∞	2.4/0.64	–	8/10/8
3-D	20.0	–	10.0	4.1/1.0	–	2/2
3-1	∞	–	∞	4.1/1.0	–	5/3/4
3-3	∞	–	4.0	4.1/1.0	–	7/2/3
3-6	∞	16/0.7	∞	4.1/1.0	–	5/4
3-8	∞	9/0.7	∞	4.1/1.0	–	8/5/8
3-12	∞	2/0.7	∞	4.1/1.0	–	7/9
3-13	∞	3/0.7	∞	4.1/1.0	–	10/10
4-1	∞	–	∞	3.0/0.74	–	3/2/3
4-2	∞	–	10.0	3.0/0.74	–	3/3/4
5-1	∞	–	∞	1.7/0.68	–	2/5
5-9	∞	6/0.7	∞	1.7/0.68	–	7/8/7
5-10	∞	4/0.7	∞	1.7/0.68	–	10/7/10
5-11	∞	16/0.93	∞	1.7/0.68	16/0.38	7/7/5

$$W_c = K_c(\tau_1 s + 1)(\tau_{\theta_2} s + 1)/\{s(\tau_2 s + 1)[s^2/\omega_{n_1}^2) + (2\xi_1/\omega_{n_1})s + 1] \times$$

$$[s^2/\omega^2{}_{sp}) + (2\xi_{sp}/\omega_{sp})s + 1]\ [s^2/\omega_{n_1}^2) + (2\xi_1/\omega_{n_1})s + 1]\}$$

Table 3.2

Neal-Smith configuration	$\Delta\varphi_P^-$, deg	$\Delta\varphi_P^+$, deg	$\Delta\varphi_P$, deg	r, dB	PR	PIOR
1A	-25	40	{-25,40}	4.6	4÷6	3
1B		34	{-20,34}	3.5	4	2
1C	-10	25	25	2.7	5	3
1D	-9	40	40	3	4÷5	3
1E		52	52	2.8	6	4
1F		58	58	3.4	7÷8	4
1G		74	74	3	8	4
2A	-50	30	{-50,30}	4.4	4÷5	3
2B	-44	30	{-44,30}	2.3	4÷5	3
2C	-44	17	{-44,17}	3.7	2÷3	1÷2
2D	-30	24	{-30,24}	1.4	2.5	1÷2
2E	-20	30	30	1	4	2÷3
2F	-16	25	25	1.7	3÷4	3
2G	-8	32	32	3.6	6÷7	3÷4
2H		36	36	2	5÷6	3
2I		62	62	7.7	7÷8	4
2J		40	40	2.4	6÷7	3
3A	-43	16	-43	1.3	4÷5	2÷3
4A	-40	35	{-40,35}	6	5÷6	4
5A	-57	35	{-57,35}	8.7	6÷7	4
6C		38	38	1.9	4	2÷3
7C	-20	13	{-20,13}	1	2÷3	2
8A	-30	25	25	1	4	2

Table 3.3

Lahos configuration($K_D = 1$)	$\Delta\varphi_P^-$,deg	$\Delta\varphi_P^+$,deg	$\Delta\varphi_P$,deg	r,dB	PR	PIOR
1-A		24	24	2.9	4÷5	2÷3
1-B		45	45	2.9	4÷5	2
1-C		48	48	2.7	4÷5	2÷3
1-1		57	57	4.6	4÷5	2÷3
1-2		59	59	4.7	5÷6	2÷3
1-4		66	66	6.4	8÷9	4
1-11		59	59	7.17	5÷6	3÷4
2-C		35	35	3.9	4	2
2-1		37	37	4.3	4÷5	2÷3
2-2		66	66	6.1	4÷5	2
2-3		49	49	5.45	4÷5	3÷4
2-4		55	55	5.9	5÷6	3÷4
2-9		64	64	7.5	5÷7	3÷4
2-10		56	56	6.2	8	4
3-C				3.9	5÷6	3
3-1		60	60	8.2	5÷7	2÷3
3-3		64	64	8.8	5÷6	3÷4
3-7		44	44	6.7	8÷9	4
4-1		35	35	1.55	4	2
4-7		63	63	4.7	4÷5	2
4-10		45	45	5.9	8÷9	3÷4
4-11		49	49	3	4÷5	3
5-4		42	42	3.5	4÷5	2÷3
5-6	-29	45	45	1	4÷5	2÷3
5-11		45	45	5	5÷6	3÷4

Lahos configuration($K_D = 0.5$)	$\Delta\varphi_P^-$,deg	$\Delta\varphi_P^+$,deg	$\Delta\varphi_P$,deg	r,dB	PR	PIOR
2-1		13	13	1.6	2	1
2-C		13	13	0.5	2÷3	2
2-10		40	40	8.42	5÷7	4
2-9		27	27	7.42	4÷5	3
1-4		50	50	5	6÷7	3÷4

Table 3.4

Have PIO configuration	$\Delta\varphi_p^-$,deg	$\Delta\varphi_p^+$,deg	$\Delta\varphi_p$,deg	r,dB	PR	PIOR
2B	-32	18	{-32,18}	2.3	3	2
2-1	-16	38	{-16,38}	1.74	4	3
2-5		40	40	4	6	3
2-7		32	32	3.6	5	4
2-8		43.5	43.5	3.5	5	3÷4
3D	-23	25	{-23,25}	1.85	4	2
3-1	-41	10	{-41,10}	2.73	4	2
3-6	-25	19	{-25,19}	.8	4÷5	3
3-8	-24	37	{-24,37}	5.7	5	3
3-12		53	53	7.85	7	4
3-13		51.5	51.5	4.8	5	4
4-1	-30	32	{-30,32}	3.25	3	2
5-1		45	45	1.33	5	3÷4
5-9		51	51	5.3	5÷7	3
5-10		52	52	7.94	6÷7	4
5-11		53	53	4.4	5	3

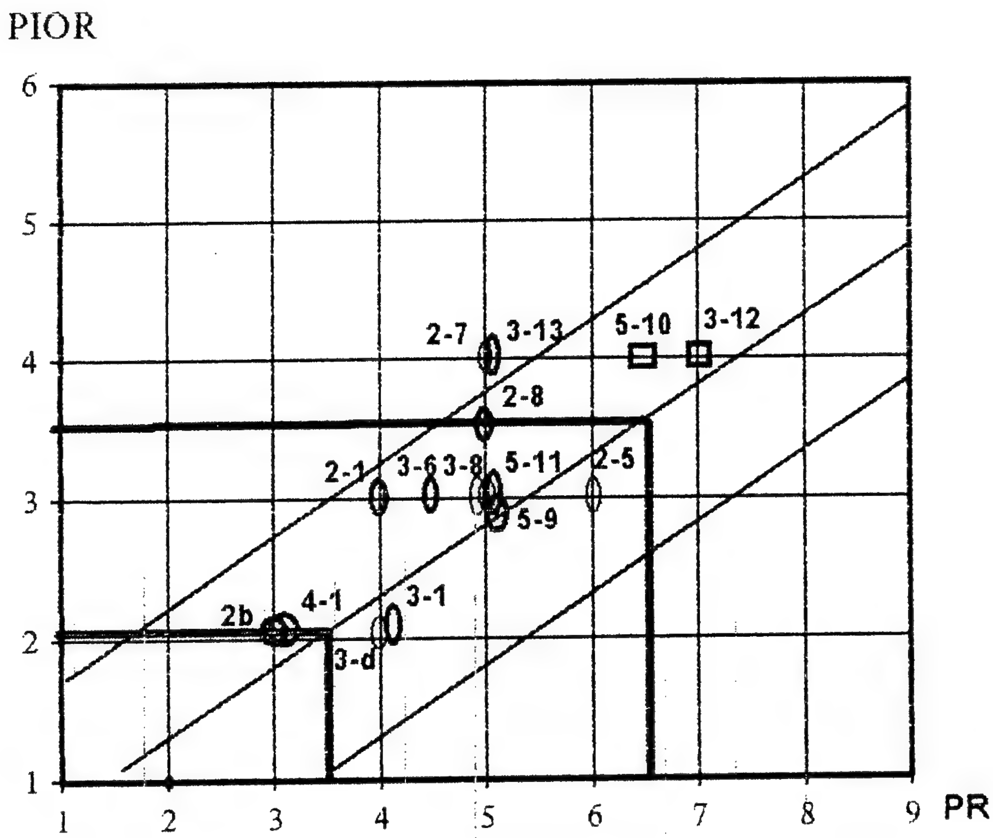


Fig.3.2. The correlation between PIOR and PR

3.2. The modified criteria for prediction of flying qualities in angular control tracking task

There are two reasons in necessity to modify the criteria for prediction of flying qualities developed in [1]

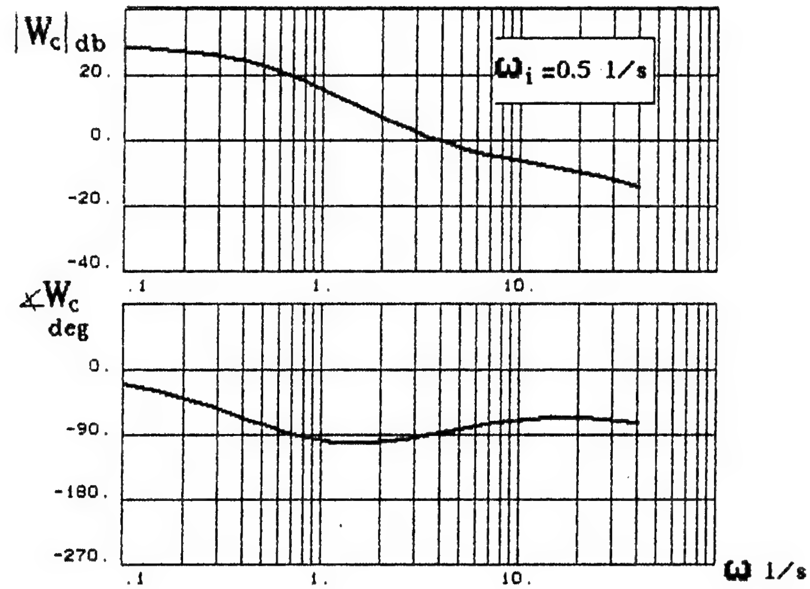
- the influence of input signal on agreement between predicted and evaluated PR,
- the influence of frequency defined the pilot compensation parameter $\Delta\varphi_p$ on pilot's workload.

The taking into account the influence of input signal

The investigations fulfilled in [1] and in this report too were carried out for the same parameters of input spectral density, $S_{ii} = \dfrac{K^2}{(\omega^2 + \omega_i^2)^2}$ for which $\omega_i = 0.5$ 1/s; $\sigma_i = 4$ sm^2. It was agreeded with actual discrete instrument tracking task used in the Neal-Smith and LAHOS flight experiments [12,16]. With goal to define the influence of input spectral density parameters there were carried out a number of experiments. In particular it was investigated the influence of input bandwidth, ω_i. Except $\omega_i = 0.5$ 1/s it was investigated the considerably lower value of this parameter, $\omega_i = 0.05$ 1/s. Because of the accuracy in calculation of frequency response characteristics deteriorates for such low bandwidth, it was ibcreased the variance of input signal σ_i^2 up to 9 sm^2 to get the accurate results of measurement in wide frequency range. According to the algorimth described in [1] it was determined optimal controlled element dynamics ($W_c^{opt}(j\omega)$ for corresponding to with $\omega_i = 0.05$ 1/s (see fig.3.3).

Such optimal dynamics was used for definition of standard characteristics - resonance peak of closed loop system, pilot phaze characterictic. Their analysis and analysis of expiments fulfilled with one of dynamics configurations (for example one of Neal-Smith configuration 1E [1] demonstrates that the usage of lower bandwidth of input spectral density causes:

- the increase of resonance peak of closed loop system;



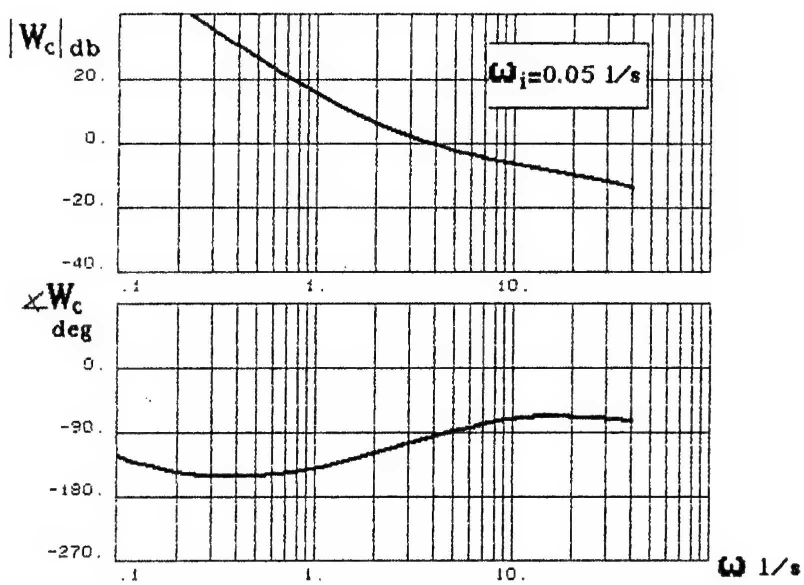


Fig.3.3. Frequency response of optimal control dynamics

- difference in value of pilot compansation parameter $W = \Delta\varphi_p = \varphi_p - \varphi_p^{opt}$ in omparison with value of this parameter obtained in [1] for case $\omega_I = 0.5$ 1/s.

According to MAI criteria - such values has to correspond to the second level of pilot ratings. At the same time pilot evaluated the investigated configuration in case when $\omega_I = 0.5$ 1/s with PR = 2. The bad accordance between the predicted and obtained pilot ratings requires to carry out the work on modification of criteria.

For thith purpose it was developed the procedures for determination of adequate conditions for evaluation of flying qualities and normalization of parameters defined MAI criteria. The first procedure was developed on bases of equations (2.8, 2.9) obtained in chapter 2. Usage of these equations for input spectral density with parameters $\omega_I = 0.05$ 1/s and $\sigma_I^2 = 9\ sm^2$ allowed to determine the values of the task performances - desired d_{des} and adequate d_{ad} performances corresponded to the considered input spectral density. These values are given in table 3.5. There are given also the values d_{des} and d_{ad} corresponding to input spectral density used in [1].

Table 3.5

	input spectral density used in [1] $\omega_I = 0.5$ 1/s; $\sigma_I^2 = 4\ sm^2$	input signal with decreased bandwidth $\omega_I = 0.05$ 1/s; $\sigma_I^2 = 9\ sm^2$
d_{opt}	1 sm	0.7 sm
d_{des}	1.75 sm	1.23 sm
d_{ad}	2.54 sm	1.78 sm

The second procedure - was assosiated with normalization of the resonance peak r and its substitution on relative value $\bar{r} = r / r_{opt}$. Where r_{opt} is a value of resonance peak of closed loop system obtained for optimal controlled element dynamics W_c^{opt}. According to [9] W_c^{opt} is a function of characteristics of input spectral density. In calculation of pilot phase compensation parameter $\Delta\varphi_p = \varphi_p - \varphi_p^{opt}$ it has to be taken

into account that the pilot's phase is a function of input spectral density parameters too.

The tendency in influence of input spectral density on pilot-vehicle system characteristics for any dynamic configuration is general and close to the tendency of its influence for optimal controlled element dynamics. Due to it there is possible to suppose that the influence of input spectral density characteristics can be avoid if the parameter r will be substitude on $\bar{r} = r / r_{opt}$. This suggestion was checked for one of the Neal-Smith configuration 1E. The results of normalization are shown in table 3.6.

Table 3.6

	input spectral density used in [1] $\omega_i = 0.5$ 1/s; $\sigma_i^2 = 4\ sm^2$	input signal density with decreased bandwidth $\omega_i = 0.05$ 1/s; $\sigma_i^2 = 9\ sm^2$
r_{opt}, dB	3.662	5.874
r, dB	6.725	9.344
$\bar{r}$, db	3.063	3.47
$\Delta\varphi$, deg	57	57

The values $\bar{r}$ and $\Delta\varphi_p$ obtained according to the developed procedures are very close for considerably different parameters of input spectral density. This fact allowed to develop the modefied criteria for prediction of flying qualities shown on fig.3.4.

<u>Taking into account the influence of frequency determined the pilot-compensation parameter</u> $\Delta\varphi_p$.

In many experiments fulfilled for different dynamic configurations it was obtained that the same values of pilot compresation parameter achieved at the different frequencies. It is obvions that in case of pilot lead compensation when $\Delta\varphi_p$ is positive ($\Delta\varphi_p^+$) the configuration W_c, for which $\Delta\varphi_p^+$ reaches at lower frequency will correspond to deteriorated flying qualities. In that case the constant time lead

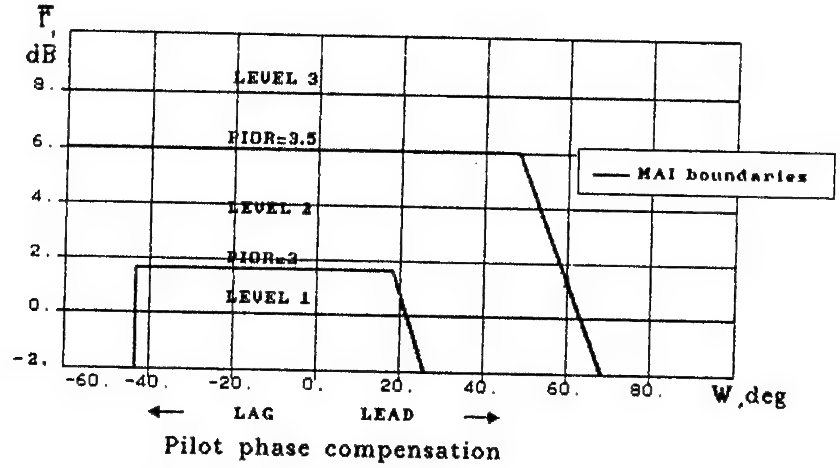


Fig.3.4. Modification of MAI criteria ($\bar{r}=r/r_{opt}$)

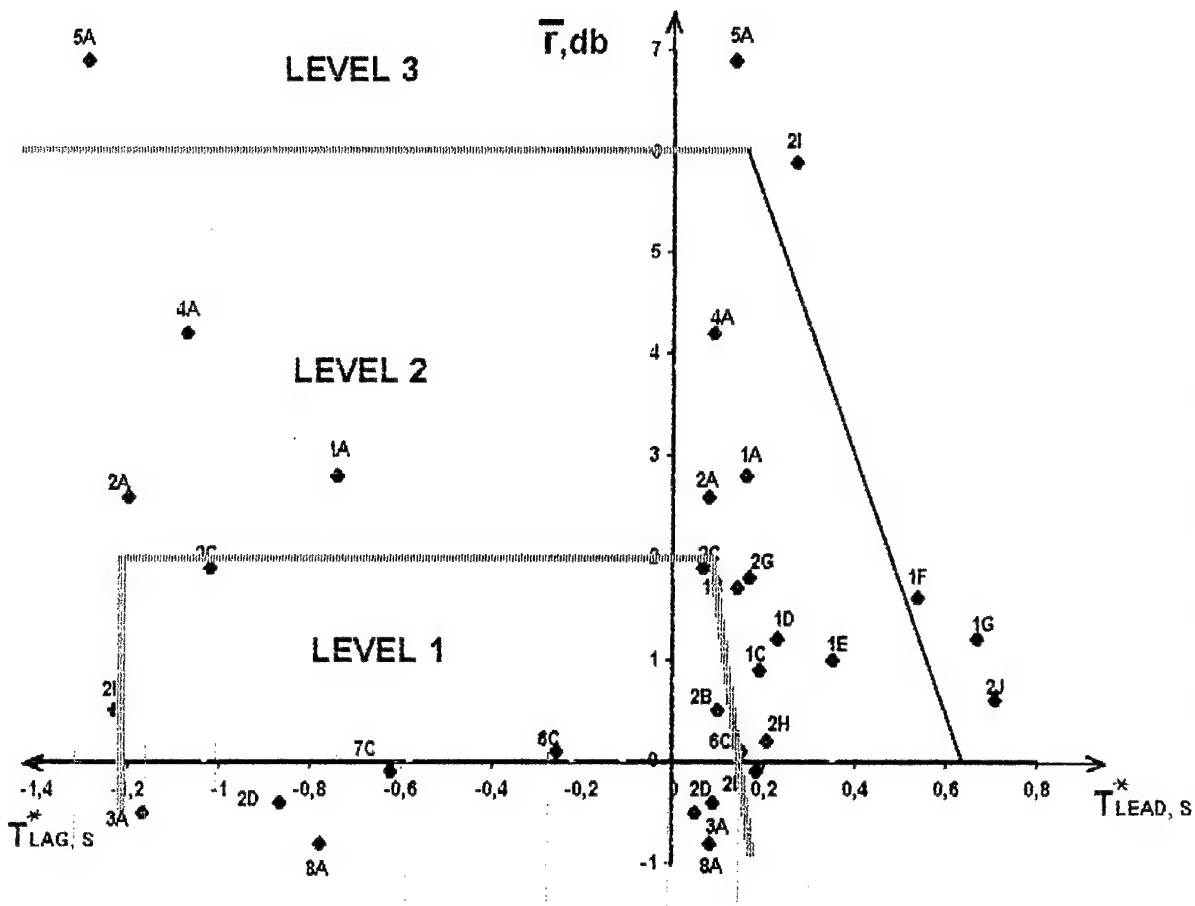


Fig.3.5. Modification of MAI criteria

conpenstation ($\overset{*}{T}_{Lead} \cong \frac{\Delta\overset{+}{\varphi}_p}{\omega_1}$) is higher in comparison with configuration W_{c_2} for which $\omega_2 > \omega_1$.

Due to this factor it was offered to use the parameter

$$\overset{*}{T}_{LAG} = \frac{\left(\Delta\overset{-}{\varphi}_p\right)_{max}}{\omega_{\Delta\overset{-}{\varphi}_{p_{max}}}} \qquad \text{and} \qquad \overset{*}{T}_{Lead} \cong \frac{\Delta\overset{+}{\varphi}_{p_{max}}}{\omega_{\Delta\overset{+}{\varphi}_{max}}}$$

instead of parameters $\Delta\overset{-}{\varphi}_{p_{max}}$ and $\Delta\overset{+}{\varphi}_{p_{max}}$ used before in MAI criteria.

Taking into account all modifications discribed above there is offered the modified criteria for the prediction of flying qualities shown on fig.3.5. There is necessary to notice very good agreement between drawn boundaries and experimentally mearused pilot-vehicle system characteristics and PR.

3.3. The development of criteria for evaluation of flying qualities in refueling task

3.3.1. The investigation of pilot-vehicle system characteristics in refueling task

Prior to development of criteria for evaluation of flying qualities in refueling task there were carried out wide investigations of influence of different variables on pilot-vehicle system characteristics.

The refueling task consists of the several stages. On each of them pilot tries to move the aircraft along the specific trajectory by control the angle of sight ε(t).

In longitudinal channel this angle is equal to $\varepsilon_V = \theta + arctg\frac{H_p}{L} \cong \theta + \frac{H_p}{L}$ and in lateral channel $\varepsilon_l = \psi + arctg\frac{\Delta Z}{L} \cong \psi + \frac{\Delta Z_p}{L}$ where H_p an Z_p are the altitude and lateral displacement of pilot station. For the different values of distance L this task is transformed from pitch control tracking task (when V/L < 1) in altitude control tracking task (V/L >> 1). In general case the controlled element dynamics in longitudinal channel is the following

$$\frac{\varepsilon_V(s)}{\delta_e(s)} = W_c^{\theta}(s)W_c^{\theta\varepsilon}(s) \tag{3.1}$$

where:

- W_c^{θ} is a pitch angle transfer function. In dependence on a type of flight control system (FCS) this transfer function can be different. The versions of such transfer function for a number of FCS are given in Chapter 1;

- $W_c^{\theta\varepsilon}$ is a kinematic transfer function $W_c^{\theta\varepsilon} = \frac{\varepsilon(s)}{\theta(s)}$.

Tacking into account on that $H_p = H_{c.g.} + \vartheta l_p$, where l_p is the distance between pilot station and c.g., and non-zero coefficient Z_{δ_e} the equation for this transfer function is the following.

$$\frac{\varepsilon(s)}{\theta(s)} = \frac{1}{L}\frac{s^2\left[-Z_{\delta_e} + l^*(M_{\delta_e} + Z_{\delta_e}M_{\dot{w}})\right] + s\left[Z_{\delta_e}(M_q + M_{\dot{\alpha}}) + l^*(Z_{\delta_e}M_W - Z_W M_{\delta_e})\right] + \left[Z_{\delta_e}M_\alpha - Z_\alpha M_\delta\right]}{s\left[s(M_{\delta_e} + Z_{\delta_e}M_{\dot{w}}) + (Z_{\delta_e}M_W - Z_W M_{\delta_e})\right]} \tag{3.2}$$

where $l^* = L + l_p$.

For $Z_{\delta_e} \approx 0$ the equation (3.2) can be simplified

$$\frac{\varepsilon_V(s)}{\theta(s)} = \frac{l^*}{L}\frac{\left[s^2 - sZ_W - Z_W\frac{V}{L})\right]}{s[s - Z_W]}, \tag{3.3}$$

It is obvions that the distance l^* (or L) influences on process of control considerably.

For considerable distance between an airplane and a basket the equation (3.3) is rather correct. In that case $l^*/L = 1$. This equations corresponds to kinematic equation in air-to-air tracking task too. For case when $V/l^* >> 1$, $\frac{\varepsilon_V(s)}{\theta(s)} = 1$. It means that angle of sight control transforms in pitch control. The decrease of L leads to transformation of controlled element dynamic when the altitude dynamics begins influence on $W_c(s)$.

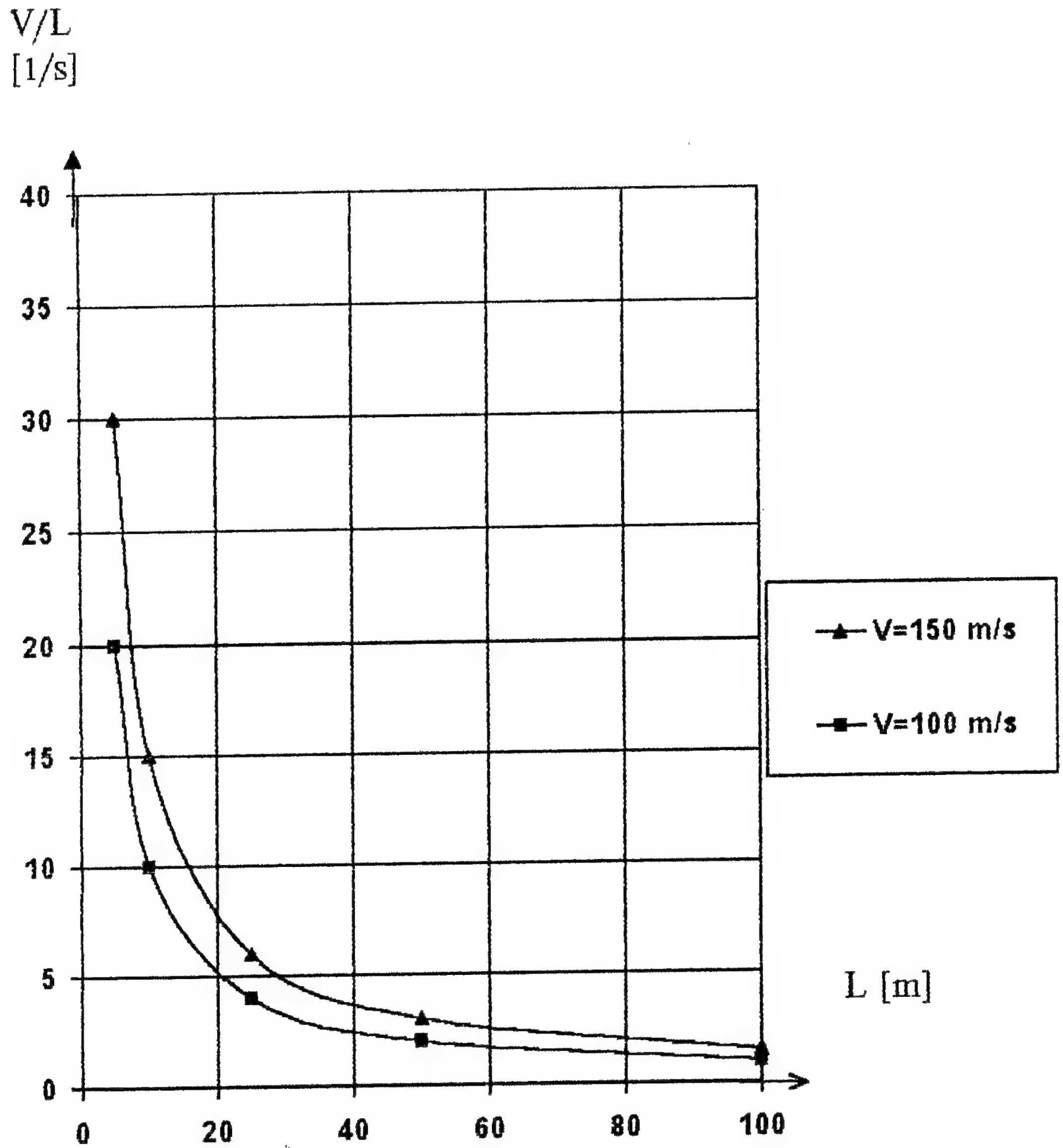


Fig. 3.6. The function V/L=f(L)

For small distance $\overset{*}{l}$ the equation (3.3 is correct only when $-\bar{Z}_e << \overset{*}{l}\,(M_{\delta_e} + Z_{\delta_e} M_{\dot{w}})$. In that case the gain coefficient of this transfer function equals to V/L. According to the fig.3.6 this ratio changes considerably in case of small L. It is well-known fact that for rapid changes of controlled element gain coefficient pilot's limitation on rapid change his own gain coefficient can cause the PIO in closed loop system.

The best way for pilot to avoid the instability in this system is to use the other output coordinate "εL" for closure the loop. This suggestion will be checked below.

When the parameters Z_{δ_e} and $\overset{*}{l}\,(M_{\delta_e} + Z_{\delta_e} M_{\dot{w}})$ are competible the additional factors begin to influence on fulfillment of refueling task. In that case the nominator of $\frac{\varepsilon(s)}{\theta(s)}$ can be presented by the following way

$$K(s^2 + 2\xi\omega_l s + \omega_l^2) \text{ where}$$

$$\omega_l^2 = \frac{Z_{\delta_e} M_\alpha - Z_\alpha M_{\delta_e}}{M_{\delta_e}\left[(L_p + l) - \frac{Z_{\delta_e}}{M_{\delta_e}}\right]}.$$

For small value L the parameters L_p and $\frac{-Z_\delta}{M_{\delta_e}}$ can influence on the controlled element dynamics considerably. Particularly for configurations with increased value of l_p the fulfillment of the refueling task is easier. The tailess aircraft configuration scheme assosiated with increase of $\frac{Z_{\delta_e}}{M_{\delta_e}}$ causes the increase of ω^2 or even to change its sigh. This peculiarity causes the deterioration in aircraft dynamics.

Supposing that in lateral motion pilot uses the aileron and keeps β = 0 the transfer function $\frac{\varepsilon_V(s)}{x_a(s)}$, ($x_a$ the lateral deflection of stick), is the following

$$\frac{\varepsilon_V(s)}{x_a(s)} = \frac{\psi(s)}{\delta_a(x)} \frac{s + \frac{V}{L}}{s} \tag{3.4}$$

where

$$\frac{\psi(s)}{\delta_a(s)} = W_{pr}\frac{\varphi(s)}{\delta_a(s)}\frac{\psi(s)}{\varphi(s)}. \tag{3.5}$$

Here W_{pr} is the prefilter in lateral channel:

$\frac{\varphi(s)}{\delta_a(s)}$ in case of absense of feedback signals proportional to φ(s) and p(s) is the following $\frac{\varphi(s)}{\delta_a(s)} = \frac{K_c}{s(s-M_q)}$. (3.6)

Supposing that β = 0 and taking into account the equation $\dot{\psi} = -\alpha_0 p - Z_W \alpha_0 \varphi$ the transfer function for $\frac{\psi(s)}{\delta_a(s)}$ can be easy defined as

$$\frac{\psi(s)}{\varphi(s)} = \frac{\alpha_0(s - Z_W)}{s}.$$

Thus $\frac{\psi(s)}{\delta_a(s)} = W_{pr}\frac{K_c \alpha_0(s - Z_W)}{s^2(s - M_q)}$. (3.7)

In case when the feedback signal is proportional to a bank angle the order of this transfer function will decreases. In principle pilot can use the pedal to change the angle ε . In that case supposing that γ = 0 the structure of transfer function for $\frac{\varepsilon \quad s}{\delta \quad s}$ is similar to $\frac{\varepsilon \quad s}{\delta_e \, s}$. In particular for case $L \quad _r$ = 0 it is equal to

$$\frac{\varepsilon \quad s}{\delta \quad s} = W_{pf}\frac{K_c \, s \; -Y_p - Y_B \frac{L}{V}}{s \quad s \; + 2\xi\omega_a s + \omega_a}.$$

The investigations of pilot-vehicle system in refueling task were carried for the different types of FCS shown in table 3.7.

The types of investigated FCS

Table 3.7

typel of FCS / channel	Conventional		RCAH		Extended RCAH		ACAH	
longitu-dinal	+		+		+		+	
lateral	+							
	control surface							
	$\delta_a \to \gamma \to \varepsilon_L$	$\delta_H \to \psi \to \varepsilon_L^*$	$\delta_a \to \varepsilon_L$	$\delta_n \to \varepsilon_L$	$\delta_a \to \varepsilon_L$	$\delta_n \to \varepsilon_L$	$\delta_a \to \varepsilon_L$	$\delta_n \to \varepsilon_L$
	feedbacks 1. - 2. $\omega_X \to \delta_a$ 3. $\gamma \to \delta_a$	feedbacks 1. -	-	-	-	-	+	-

* - the limited numder of results on investigation of this FCS ave not given in this report

There were investigated a wide set of different dynamic configurations (see tables 3.8, 3.9, 3.10) considered before in reports [2] and [17] where the refueling task was studied. In table 3.9 there are given the Neal Smith configurations investigated before in [17]. In table 3.8 there are given so-called Have GAS configurations investigated in [2]. Except these configurations there were considered some additional configurations (in longitudinal and lateral channels) given in table 3.10.

Except the dynamic configurations there were investigated the influence of controlled element gain coefficient K_c, variance of basket displacement $\sigma^2_{H_B}$ defined input signal $\sigma^2_i = \frac{\sigma^2_n}{L^2} a^2$, where a is a distance between a pilot and windshielglass. The variance $\sigma^2_{H_B}$ was changed from 0 up to 0.64 m^2; the damping ratio in short period motion ξ_{sp}; the distance l. The last parameter changed in the range (120 ÷ 140) ÷2 m. In majority of experiments fulfiled in unstationary conditions the approach velolity was equal to 1 m/sec. With goal to get the accordance with the results of research [2] and [17] it was taking into account the different velocities if aircraft in these

Table 3.8

Type of FCS				
RCAH	R1	R2	R3	R4
Exterded RCAH	RX1	RX2	RX3	RX4
ACAH	A1	A2	A3	A4

$$W_C^{\Theta} = \frac{\Theta(s)}{C(s)} = W_{pr} \frac{k_C(S + 1/T_q)}{S(S^2 + 2\xi\omega S + \omega^2)} W^*$$

where W^* -the approximation of additional high frequency aircraft describing function. The basic configurations of $W_C^{\Theta}(j\omega)$ (for Wpr=1) are given on fig. 3.29.

W_{pr}:

RCAH $\quad W_{pr}(S) = 1$

Exterded RCAH $\quad W_{pr}(S) = \dfrac{S + 1.5}{S + 1/T_q}$

ACAH $\quad W_{pr}(S) = \dfrac{S}{S + 1/T_q}$

Configuration	$1/T_q$ (1/s)	[ξ,ω] (-,1/s)
R1,RX1,A1	2.0	[0.7,2.6]
R2,RX2,A2	2.5	[0.7,3.65]
R3,RX3,A3	3.0	[0.7,4.82]
R4,RX4,A4	3.5	[0.7,6.21]

Table 3.9

$n_{\alpha} = 18.5 g/rad \qquad 1/T_{\Theta_2} = 1.25$ 1/s

conf.	1D	2D	4A	5A	1B	2A	1E	4D	5D
$1/\tau_1$	∞	∞	∞	∞	2	2	∞	∞	∞
$1/\tau_2$	∞	∞	∞	∞	5	5	5	2	2
ω_{sp} / ξ_{sp}	2.2 0.7	4.5 0.72	4.5 0.29	4.7 0.18	2.2 0.7	4.5 0.72	2.2 0.7	4.5 0.29	4.7 0.18

investigations. Due to this circumstence for the configurations given in table 3.9 it was V = 174 m/s, and for configurations given in table 3.8 it was V = 145 m/s.

The experiments were carried out at the MAI workstation with participation of two operators having the considerable expirience in fulfilment of tracking task. The information demonstrated on the display consisted of the drogue with diameter equal to 0.8 m and central diameter for the probe close to 0.2 m. Except the basket it was drawn the outlined picture of tanker. In some experiments it was shown the pitch angle. The end of droge was represanted as a center of cross (see fig.3.7). The size of the backet was changed as a function of 1/L. The basket's displacement was the random input signal characterized by the second order filter

$$S_{ii}(\omega) = \frac{K^2}{(\omega^2 + \omega_I^2)^2}.$$

All experiments were fulfilled in stationary (L = const) and unstationary (L = var) conditions.

The experiments in stationary conditions were carried out to expose the main regularities and influence of investigated variables on pilot-vehicle system characteristics.

In these experiments there were measured the following characteristics.

1. Frequency responce characteristics

- pilot describing function $W_p(j\omega)$,
- pilot-vehicle open-loop describing function $W_{OL}(j\omega)$,
- closed-loop describing function $W_{CL}(j\omega)$.

2. The spectral density of all signals (input, error, control aircraft output) and normalyzed remnant spectral density

$$\bar{S}_{n_e n_e} = \frac{S_{n_e n_e}}{\sigma_e^2}.$$

3. The variances of all signal and their correlated and uncorrelated with input signal components.

In each experiments fulfilled in unstationary conditions the final erros (the error at the moment of contact) between center of probe and droque (e_Z, e_y and total $e = \sqrt{\left(e_Z^2 + e_y^2\right)}$ were measured. For each experiments there were carried out no less

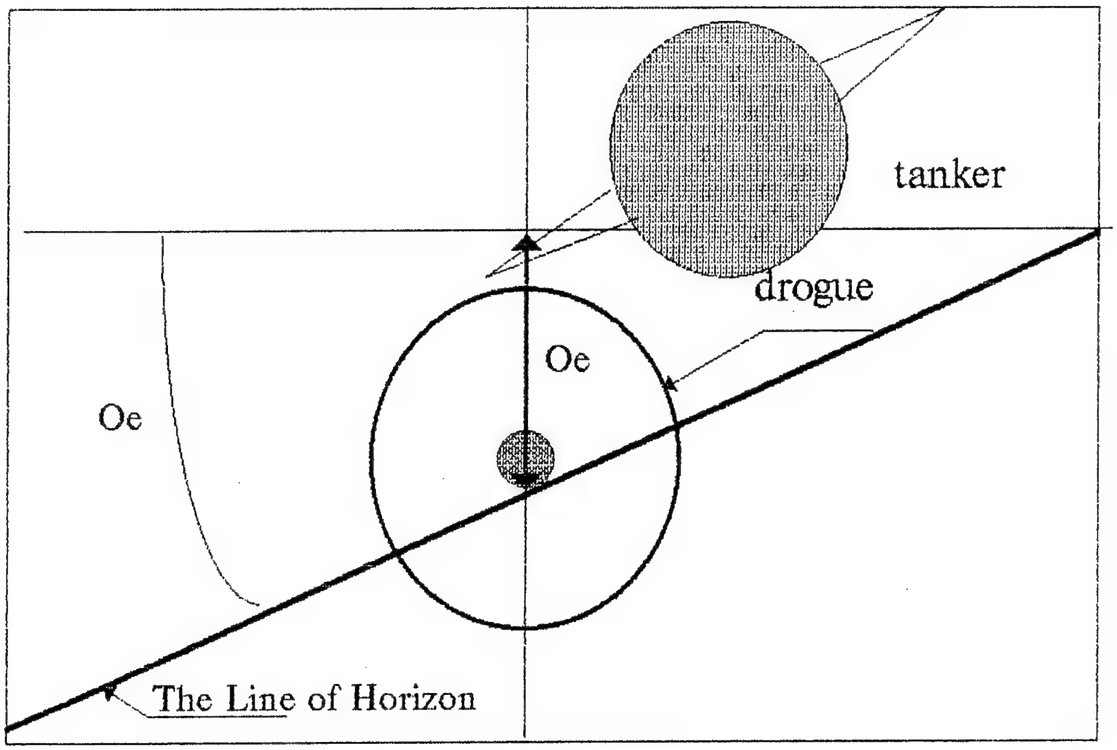


Fig.3.7. Display

then 10 runs, what allowed to evaluate the prolability of successful attempt, P. The last was defined as a ratio of successful attempts, m, to the total number of attempts, n:

$$P = \frac{m}{n}. \tag{3.8}$$

a. Longitudinal channel

It was supposed that the successful attempt takes place when error e ≤ r. Because of there is no any publested information it was proposed that $r = \frac{d_{des}}{2}$. The value d_{des} according to 3.3.2 was equal to 0.4 m.

a.1. The influence of distance L

The characteristic parameter for the refueling task (as for air-to-air tracking task too) is the distance l^* between pilot and basket. This parameter influences at last on 4 task variables of pilot-vehicle system:

- controlled element dynamics, $W_c = \frac{\varepsilon_V}{x_p}$. According to (3.3) this dynamic depends on parameter $l^* = l_p + L$,
- input signal i(t). This input signal is a projection of the basket motion $H_B(t)$ on the windshield glass $i(t) = \frac{H_B(t)}{L(t)} a$,
- percieved radious of basket $\bar{r}_p = \frac{r_B}{L(t)}$,
- kinematic transfer function $\frac{\varepsilon_V}{\bar{\varepsilon}_V}$ where $\bar{\varepsilon}_V$ in asangle of sight ε_V, where $\varepsilon_V = \theta + \frac{H}{\bar{L}^*}$, $\bar{L}^*$ is the distance between pilot and tanker. This dynamics can influence on pilot-vehicle system when pilot close coordinate $\bar{\varepsilon}_V$ in the inner loop. The reason of such pilot's strategy will be discussed loter.

The influence of these specific variables was investigates for the different types of flight control system. This study allowed to understand better the regularities taking place in pilot vehicle system in fulfilment of different stages of refueling task.

The influence of distance L was investigated basiculy for the configurations shown in table 3.6. The main part of experiments was fulfilled for longitudinal channel for the range of parameter L covered all stages in approach of aircraft and a basket.

<u>The influence of controlled element dynamics</u> $W_c = f(\overset{*}{l})$. The part of experiments fulfilled in stationary conditions was carried out for the constant variance of input signal ($\sigma_i \neq f(L)$) to expose the influence of controlled element dynamics as a function parameter $\frac{V}{\overset{*}{l}}$ ($W_c = f\left(\frac{V}{\overset{*}{l}}\right)$). The experiments demonstrated the considerable influence of this parameter on all measured pilot vehicle system characteristics for all types of FCS excapt ACAH type of system realized by the prefilter $W_{pr} = \frac{Tp}{Tp+1}$.

From the data shown on fig.3.8 obtaines for conventional aircraft there is seen that the increase of parameter V/L from 2 up to 10 1/s the variance of error in longitudinal channel σ_e^2 increases in 3 times. It is accompanied by apperance (at V/L $\geq 0.5 \div 1$) the additional resonance peak in low frequency range in closed loop system frequency response. Its value increases when V/L increases. At V/L = $5 \div 10$ the low and high frequency peaks are close. The further approach to basket leads to disappearence of high frequency peak at all. As for ACAH type of system, realized by prefilter W_{pr}, the decrease of distance $\overset{*}{l}$ leads even to decrease of error (its variance decreases up to 30 % when V/L changes from 2 up to 16 , see fig.3.9).

The results of mathematical modelling fulfilled by use the pilot OCM demonstrated good accordance with discribed above results (see fig.4.31).

The simular effect takes place in lateral channel too. In detail it will be discussed later.

<u>The influence of variance of input signal</u> ($\sigma_e^2 = f(L)$). The approach to the basket is accompanied by the increase of variance of input signal $\sigma_i^2 = \frac{\sigma_{H_B}^2}{L^2} a^2$, where $\sigma_{H_B}^2$ -

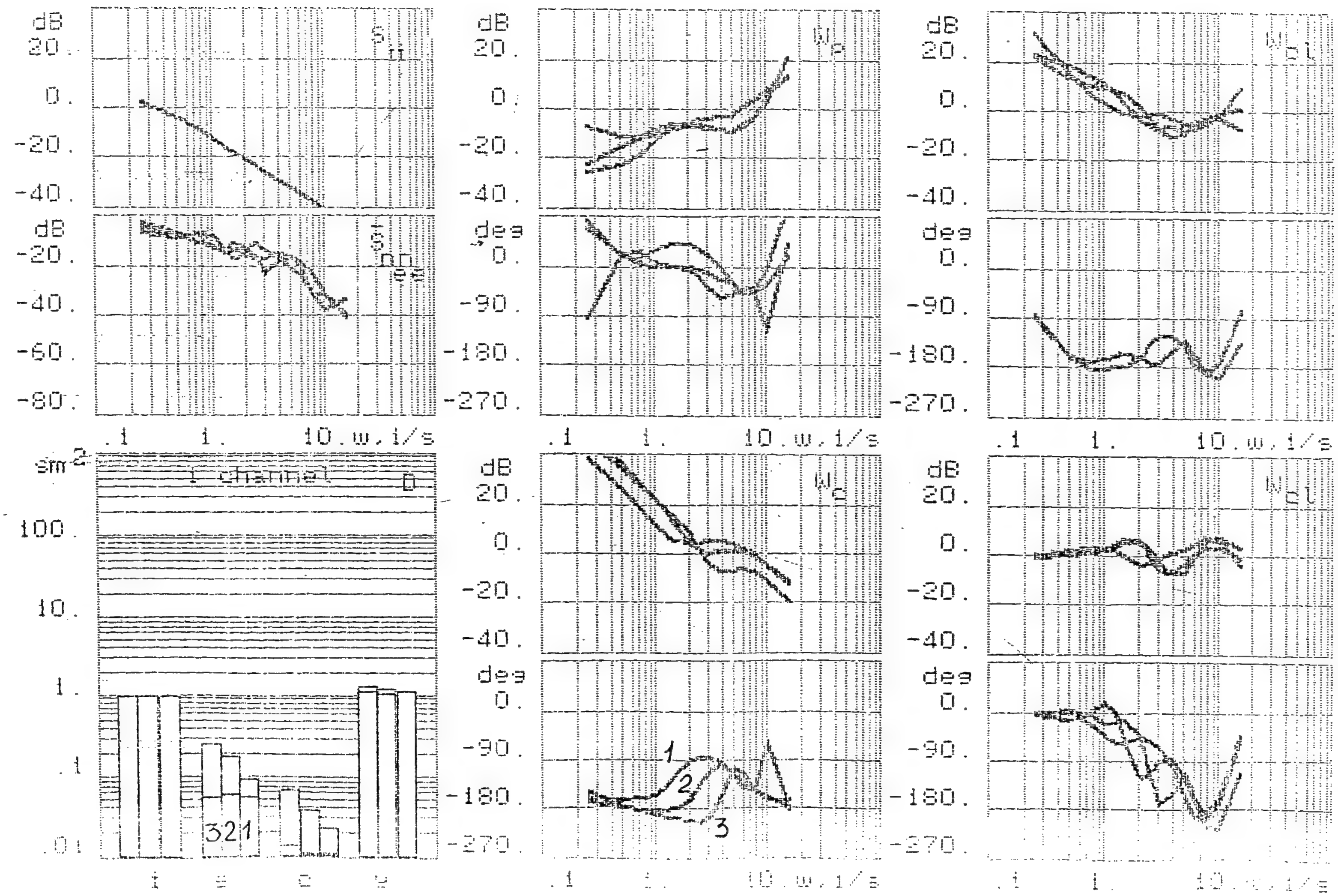


Fig.3.8. The influence of the distance (V / I^*) in longitudinal channel for conventional FCS

1. $V / I^* = 2$, 1/s; 2. $V / I^* = 5$, 1/s; 3. $V / I^* = 10$, 1/s

1 - V/L=2
2 - V/L=5
3 - V/L=10

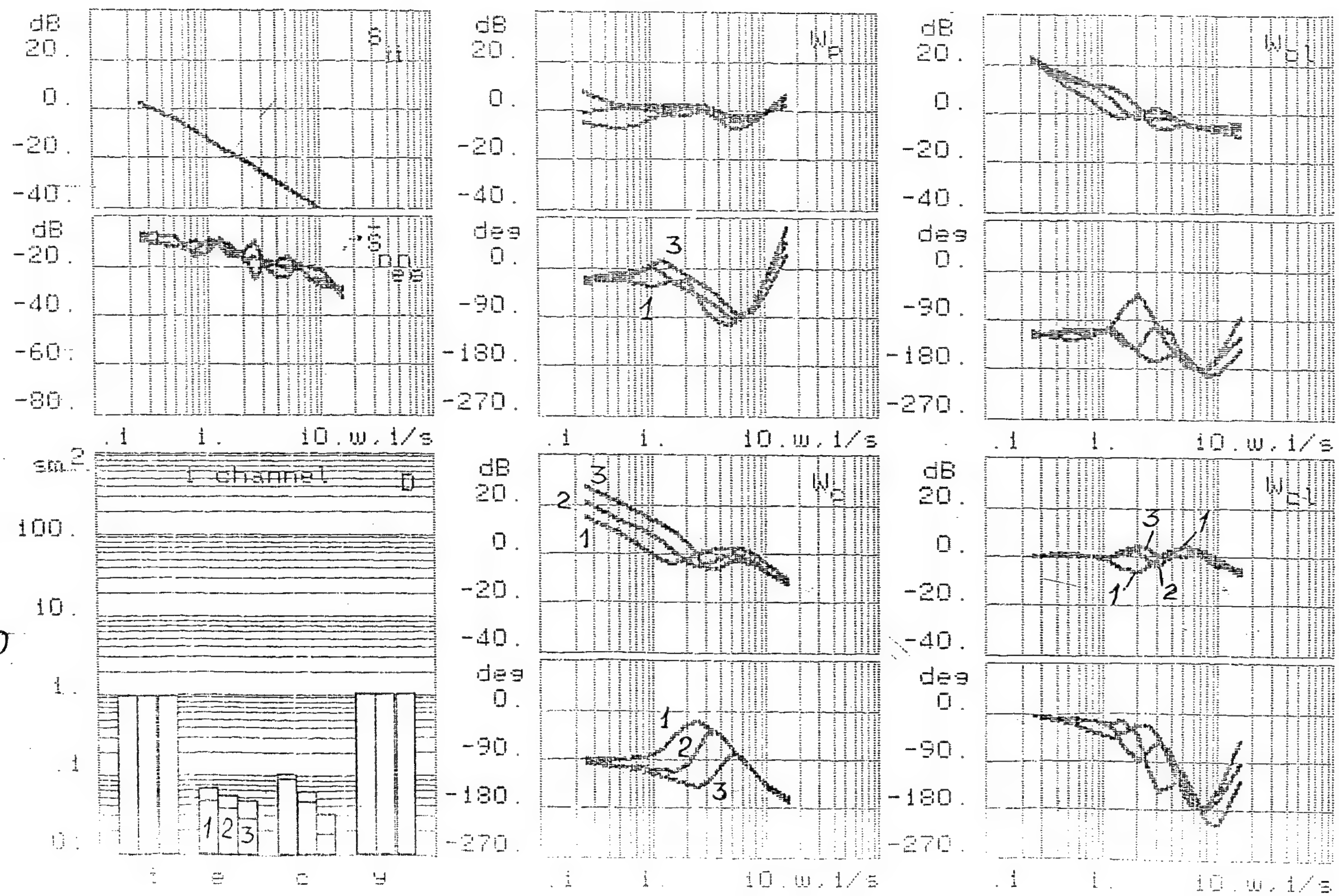


Fig.3.9. Influence of the dustance (V / l^*) in longitudinal channel for ACAH system

1. V / l^*=2, 1/s; 2. V / l^* = 5, 1/s; 3. V / l^* = 10, 1/s

variance of basket displacement) and as a consequence the by the variance of error too (see fig.3.10). Investigations demonstrated that in the range L = 50 - 10 m the normalyzed variance of error σ_e^2 / σ_i^2 stayed close to constant. For higher distance the nonlinear effects begin to influence on results and increase σ_e^2 / σ_i^2. For very small distance L < 5 the ratio σ_e^2 / σ_i^2 increases again because of an extreme deterioration of aircraft flying qualities and conditions of perception. The last is assosiated also with too high input signal used in research σ_i = 0.8 m. Because of these circumstances the variance of error was close to σ_i^2 for L = 2 m (case when $I_p \cong 0$). As for pilot-vehicle system characteristics obtained in contition when $\sigma_i = f(L)$, they corresponded to the characteristics (obtained in assumption $\sigma_i \neq f(L)$ quentitarly in the range L = 50 - 10 m and qualitevly outside this range. The slight difference in pilot-vehicle system characteristics was assosiated with different gain coefficients used in two groups of experiments, when $\sigma_i^2 = f(L)$ or $\sigma_i^2 \neq f(L)$.

The high values of error signals taking place at small distance L and for high values of variance σ_i^2.

The influence of piloting technique. The main part of experiments was fulfilled in conditions of single loop system, when operator had ability to see on display screen only a basket with sizes changing as a function of L and zero error position. The demonstration of additional information didn't expose any change in pilot-vehicle system characteristics. Only in precontact position when L is close to 2 m it was noticed (only for very high values of variance of basket displacement) the change in pilot-vehicle system characteristics and pilot's commends, demonstrated his desire to use the information about the position of aircraft in relation to tanker (it means the angle $\varepsilon_V = \vartheta + \frac{\Delta H}{\bar{L}^*}$, where $\bar{L}^*$ is distance between the pilot and tanker) or pitch angle. On fig.3.11 there are shown the pilot-vehicle system characteristics obtained for single and dual - pilot vehicle system loop when the tanker and pitch angle were

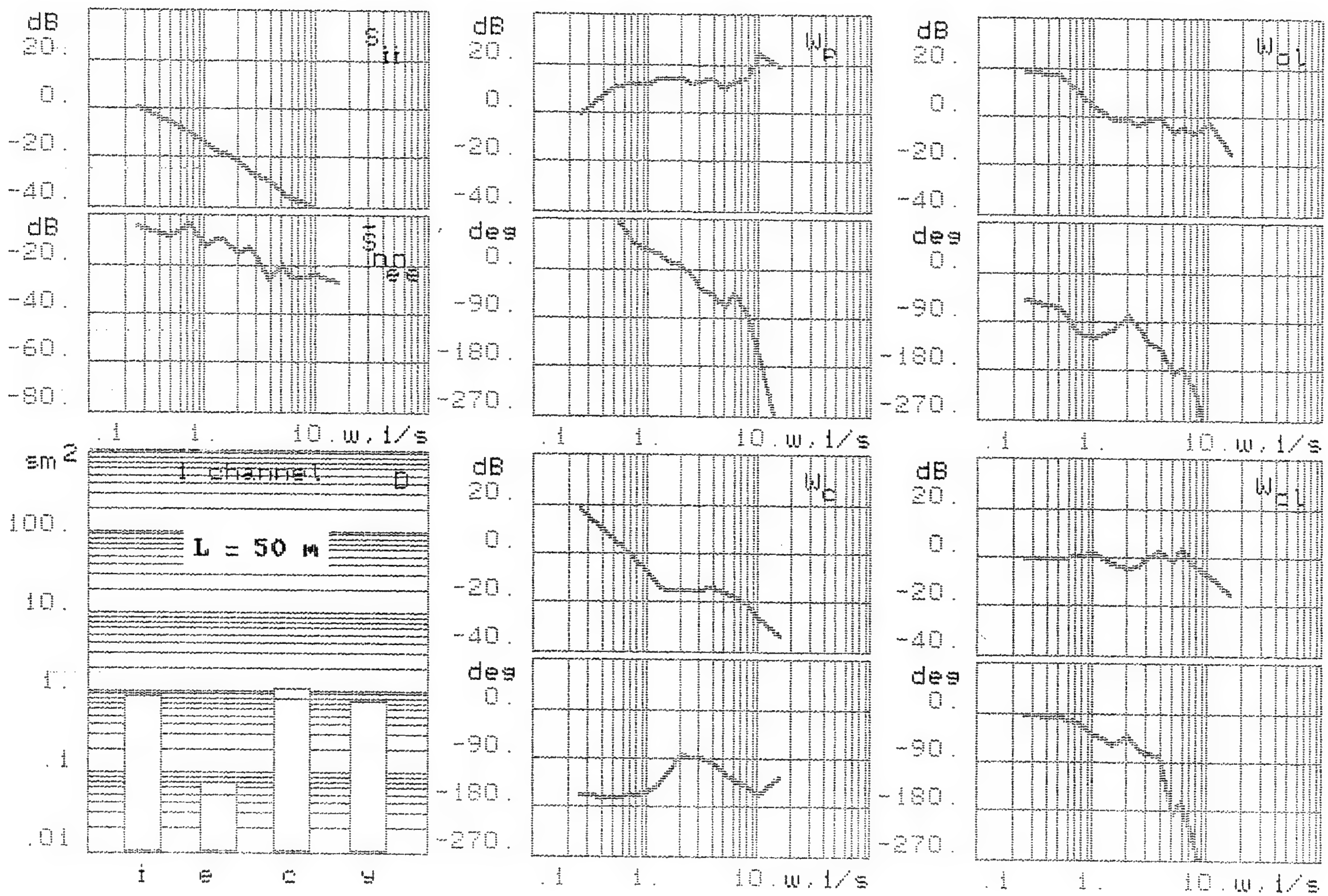


Fig.3.10.a. The influence of $\tilde{D}_i = f(L)$ and $W_c = f(L)$

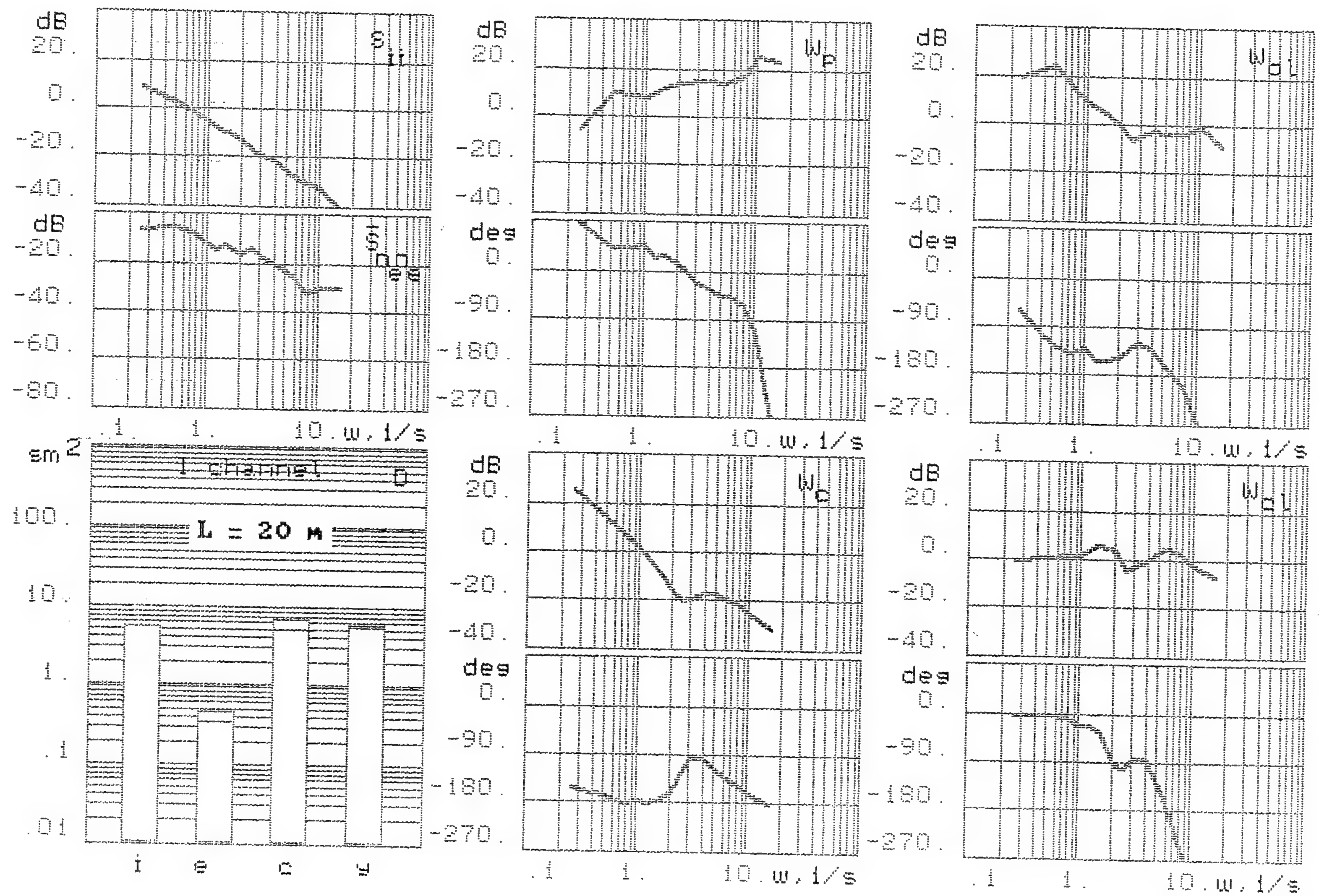


Fig.3.10.b. The influence of $\sigma_i = f(L)$ and $W_c = f(L)$

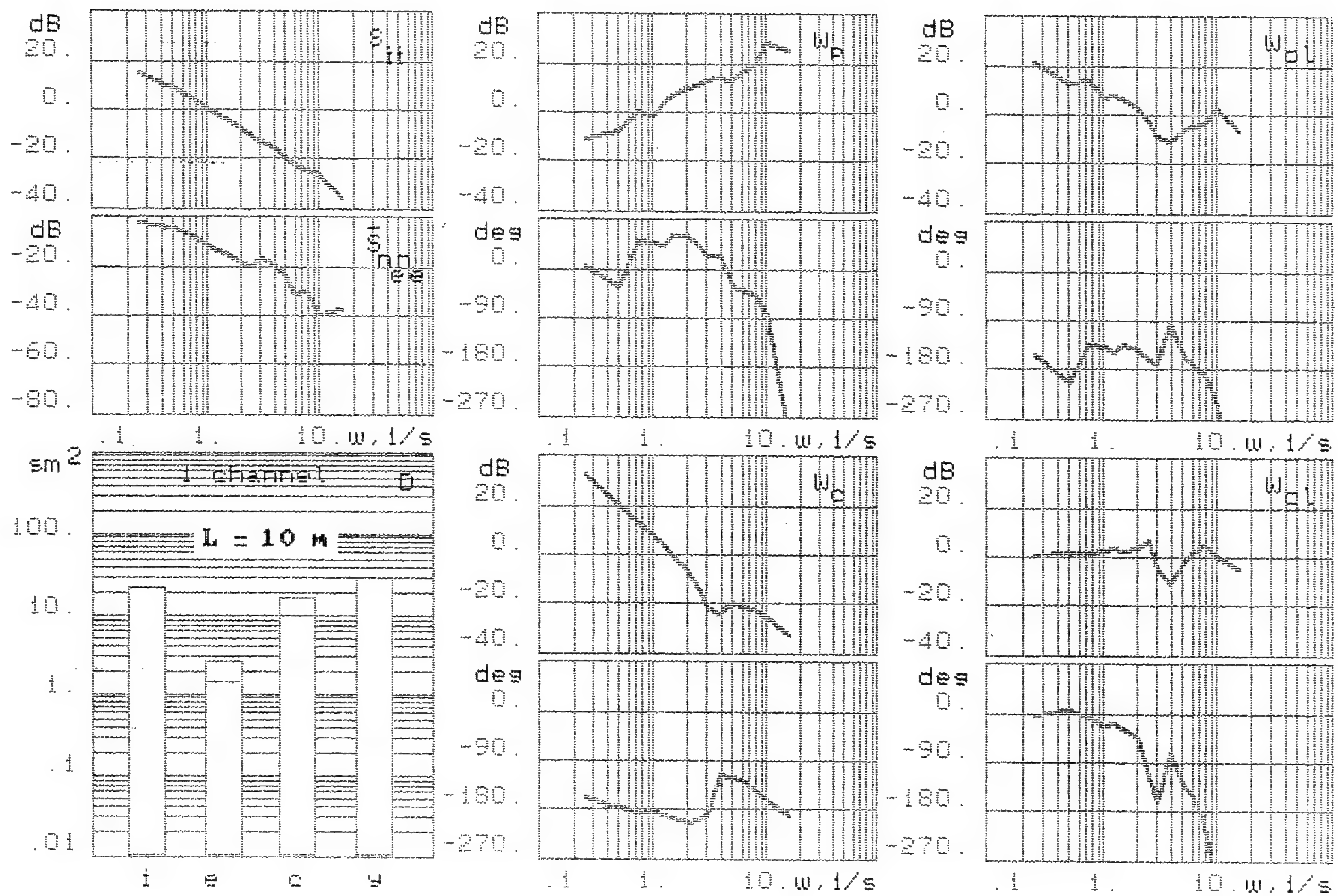


Fig.3.10.c. The influence of $\tilde{D}_i = f(L)$ and $W_c = f(L)$

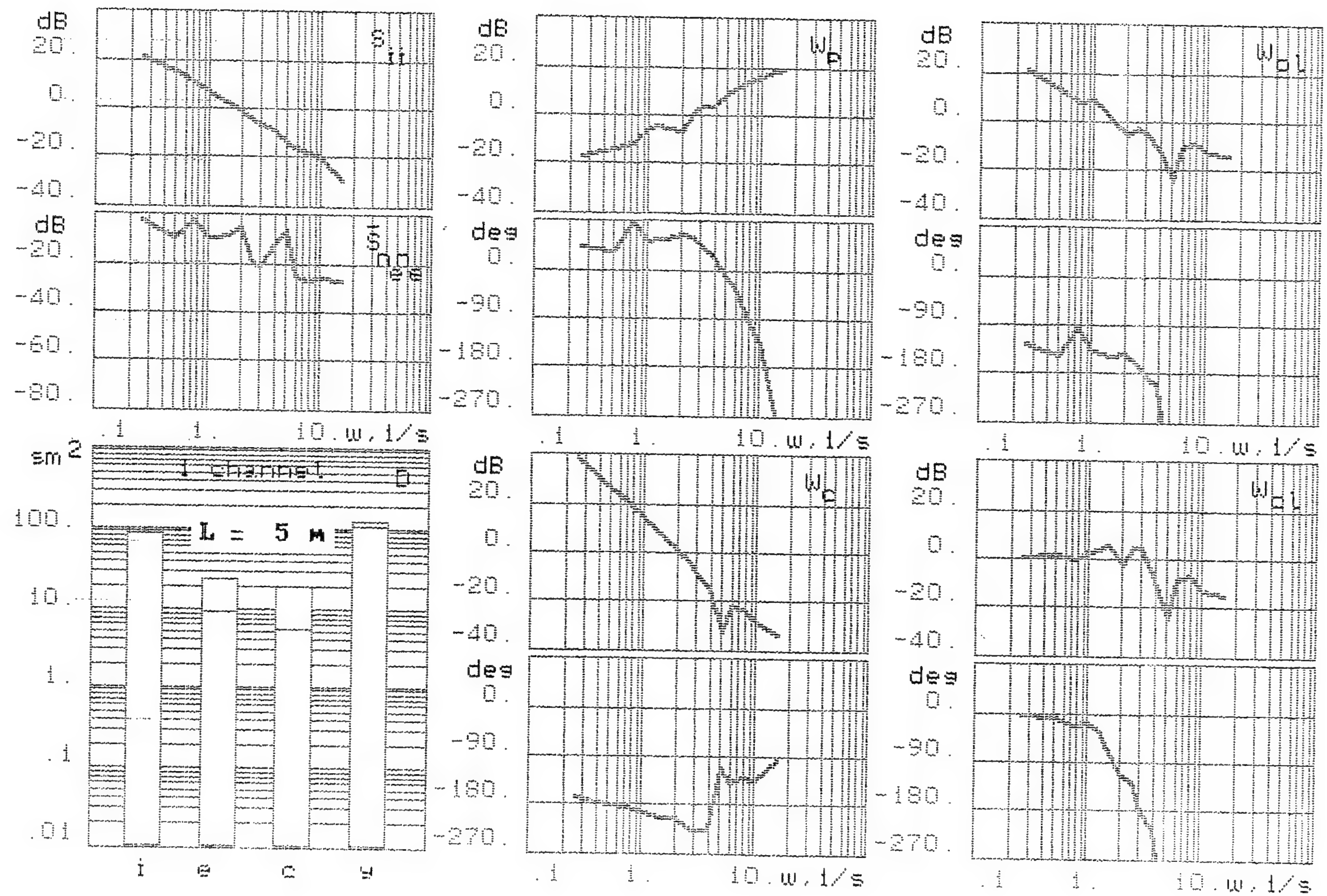


Fig.3.10.d. The influence of $\tilde{D}_i = f(L)$ and $W_c = f(L)$

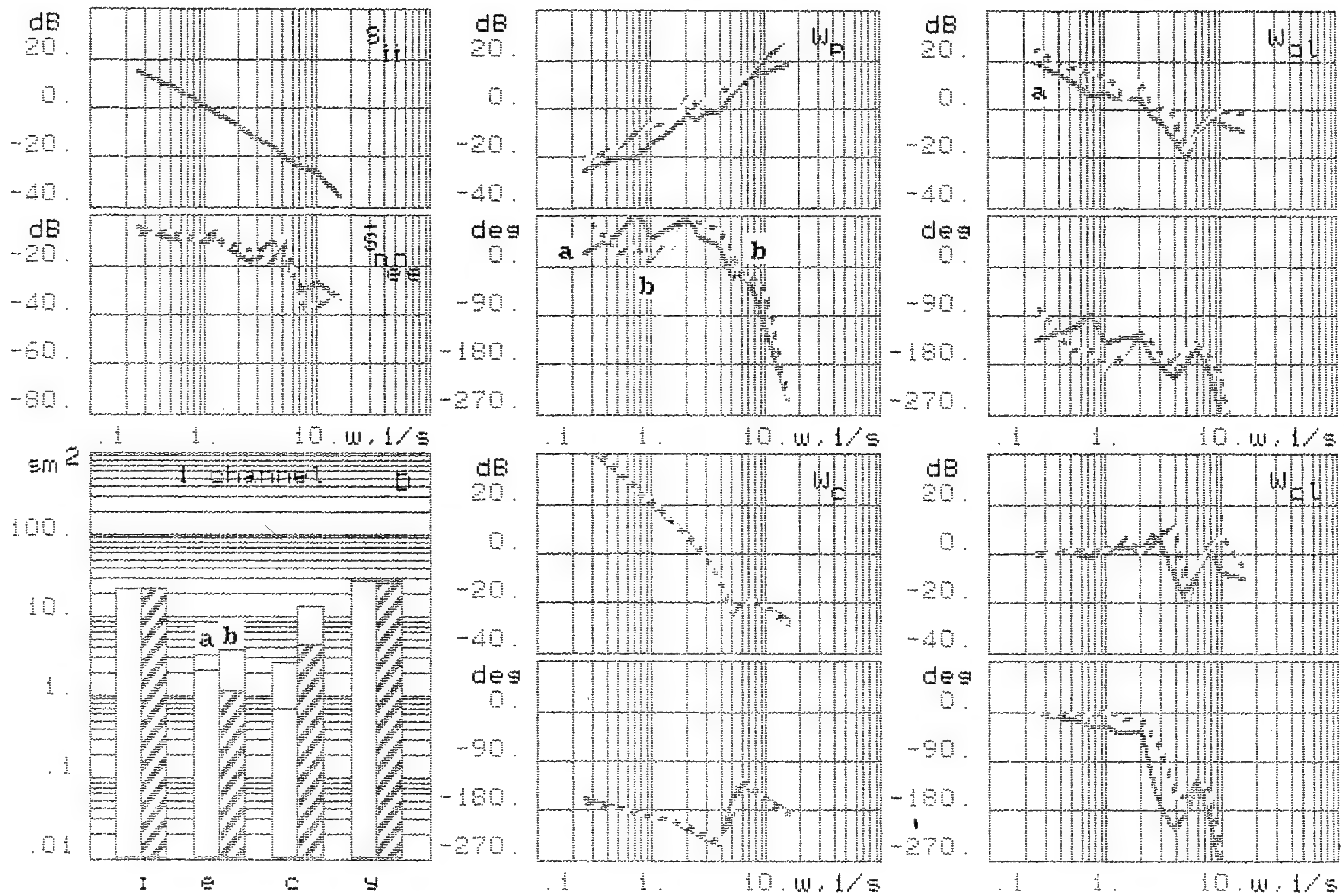


Fig.3.11. Different piloting technique (high values of Kc)
a – pilot uses the information about $\bar{E}_y$
b – pilot doesn't use the information about $\bar{E}$

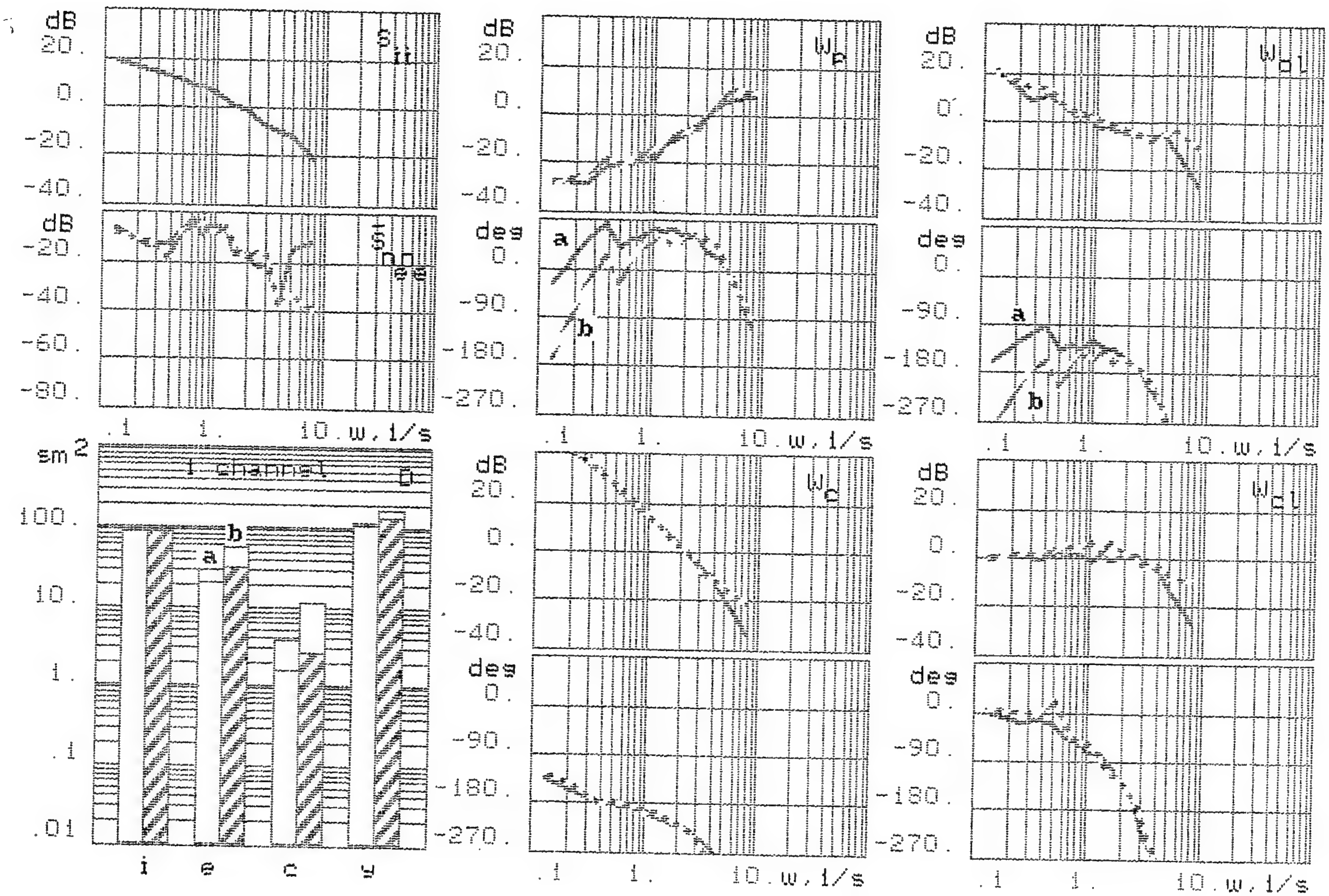


Fig.3.12. Different piloting technique (high values of input signal $\bar{\sigma}_{H_B}$ =0.8m)
a - pilot uses the information about $\bar{\varepsilon}_v$
b - pilot doesn't use the information about $\bar{\varepsilon}_v$

demonstrated on display. The results demonstrated:

- the considerable decreases of variance of error,
- the increase of pilot phase compensation in low frequency range,
- decrease of resonanse peak of closed-loop system -

in case of dual loop.

The closure of additional loop on coordinate $\bar{\varepsilon}_V$ for precontiact position took place and in case of high controlled element gain coefficient. The results shown on fig.3.12 demonstrates this effect. This results corresponds to pilot comments given in [17], reflecting pilot behavior in organizing of dual loop in the final stage of refueling for case of increased gain coefficient.

In cases of optimal gain coefficient and moderate values of basket's vertical displacements (for $\sigma_{H_{B.}} \leq 0.1 \div 0.4$ m) the experiments didn't expose pilot's desire or any actions to use the additional information to improve pilot-vehicle system characteristics.

<u>The influence of size of basket.</u> It was shown above that approach to the basket leads to increase of its size of projection. There is no any references about kind of information - linear or augular, perceived by pilot at small distance $\overset{*}{l}$. In case if pilot uses angular information about error the gain coefficient of controlled element dynamics $W_C = \frac{\varepsilon_V}{\delta_e}$ (where $\varepsilon_V \cong \frac{\Delta H}{\overset{*}{l}}$) is increased considerably when L decreases. In case of perception of linear information about the error the gain coefficient of controlled elemrnt dynamics, $W_C \cong \frac{\Delta H}{\delta_e}$, practically is not dependent on the distance.

The last case can be more prefareble for a pilot, because of there is not necessity to adapt his gain coefficient. With goal to define the perceived coordinate there were carried out several experiments with constant and variable projection's sizes of basket. The results of time processes shown on fig.3.13, 3.14 demonstrate that in case of constant size of basket's projection the pilot actions have completely different type and unstable processes takes place at small destance of L. For the other case of representation of a basket the control procces is stable practically up to the contact between probe and droque. This results demonstrate that in the last case pilot actively

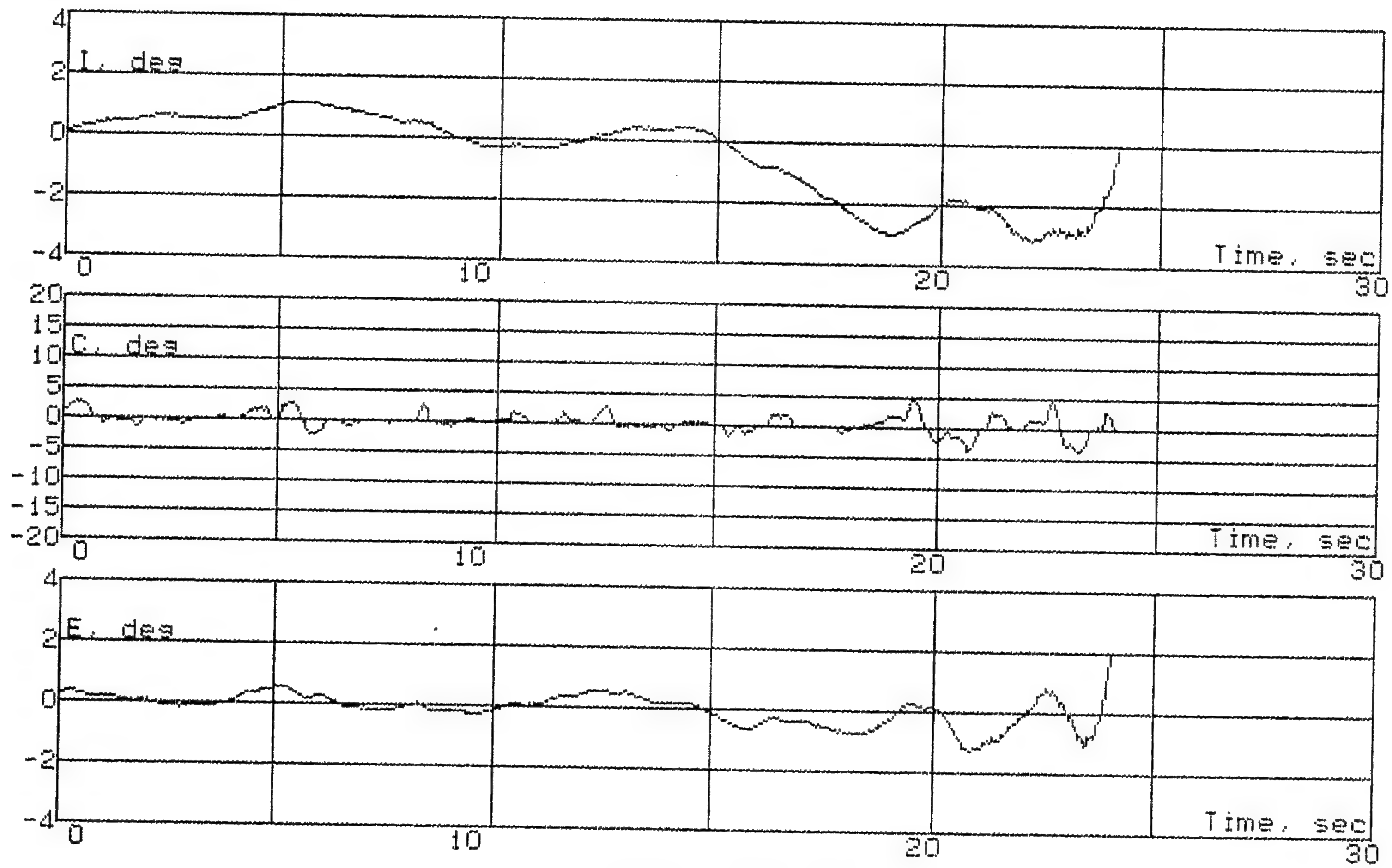


Fig.3.13. Experiment with change of drogue size ($\dot{L}$ = 1 m/sec)

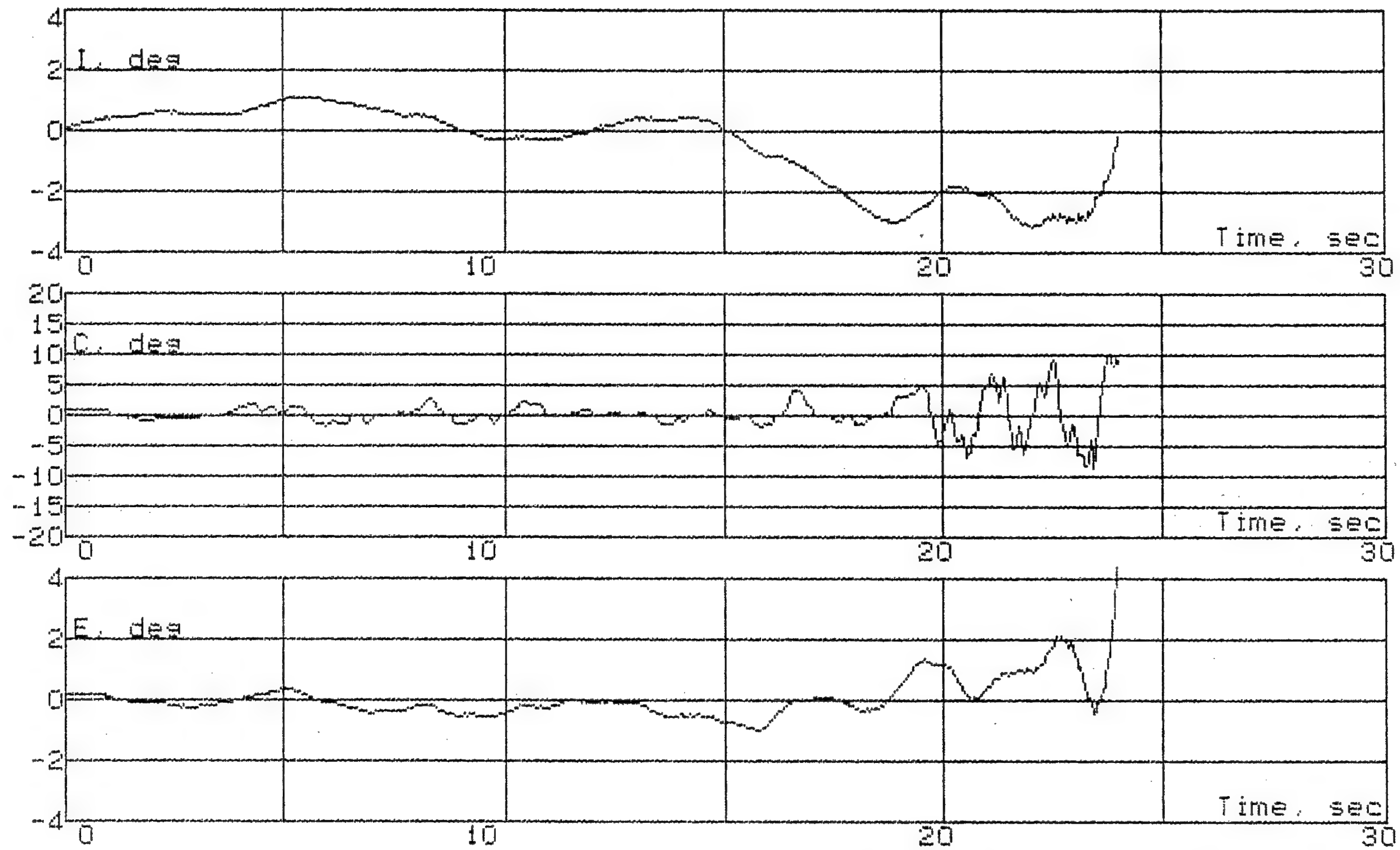


Fig.3.14. Experiment without change of drogue size ($\dot{L}$ = 1 m/sec)

uses the information about the change of projection's size. This results allows to suppose that at the last stage of approach to the basket pilot perceives the linear coordinate.

a.2. The influence of different types of FCS.

The conventional type of FCS. It was shown above that for the conventional type of FCS pilot-vehicle system characteristics are rather sensitive to the change of parameters V/L. The improvement in accoracy for this sysrem can be achived only by the corresponding choice of gain coefficient and dynamic parameters ω_{sp} and ξ_{sp}. The influence of damping ratio in this task was investigated below. In chapter 1 it was analyzed the results of report [2] demonstrated the disagrement between the evaluations of flying qualities obtained by use ω_{γ} and ω_{θ} criteria for configurations with decreased damping ratio.

In current research this result was checked by measurements of pilot-vehicle system characteristics for conventional configuration with $\xi = 0.7$ and 1.4, L = 5 m, $-Z_W$ = 1.25 and ω = 4.9 1/s, V = 100 m. For higher distances the aircraft dynamics corresponds to dynamics in air-to-air tracking task. It was shown in chapter 1 that an increase of damping ratio in this task leads to improvement of accuracy and PR too. The experiments fulfilled for small distance L demonstrated the opposite effect. The decrease of damping ratio twice caused the decrease of error in two times and resonance oeak in closed-loop pilot-vehicle system up to 2.5 dB (fig.3.15). All these effects are assosiated with the improvement in phase of controlled-element-dynamics.

The use of RCAH type of flight control system is accorrpanted by decrease in the accuracy for high and intermediate values of V/L in comparison with aircraft with conventional type of response (see fig.3.16, 3.17, 3.18).

The decrease of error was achieved only for high values of input signal and for V/L = 0.5 (fig.3.16) which are more typical for air-to-air tracking task.

The following decrease of distance L (for V/L ≥ 2) leads to increase of error aircraft with RCAH type of flight control system and the low frequency resanance peak in closed-loop describing function. For example in case V/L = 5 1/sec its value for aircraft with RCAH system is higher on 2.5 dB, and variance of error twice more (fig.3.19).

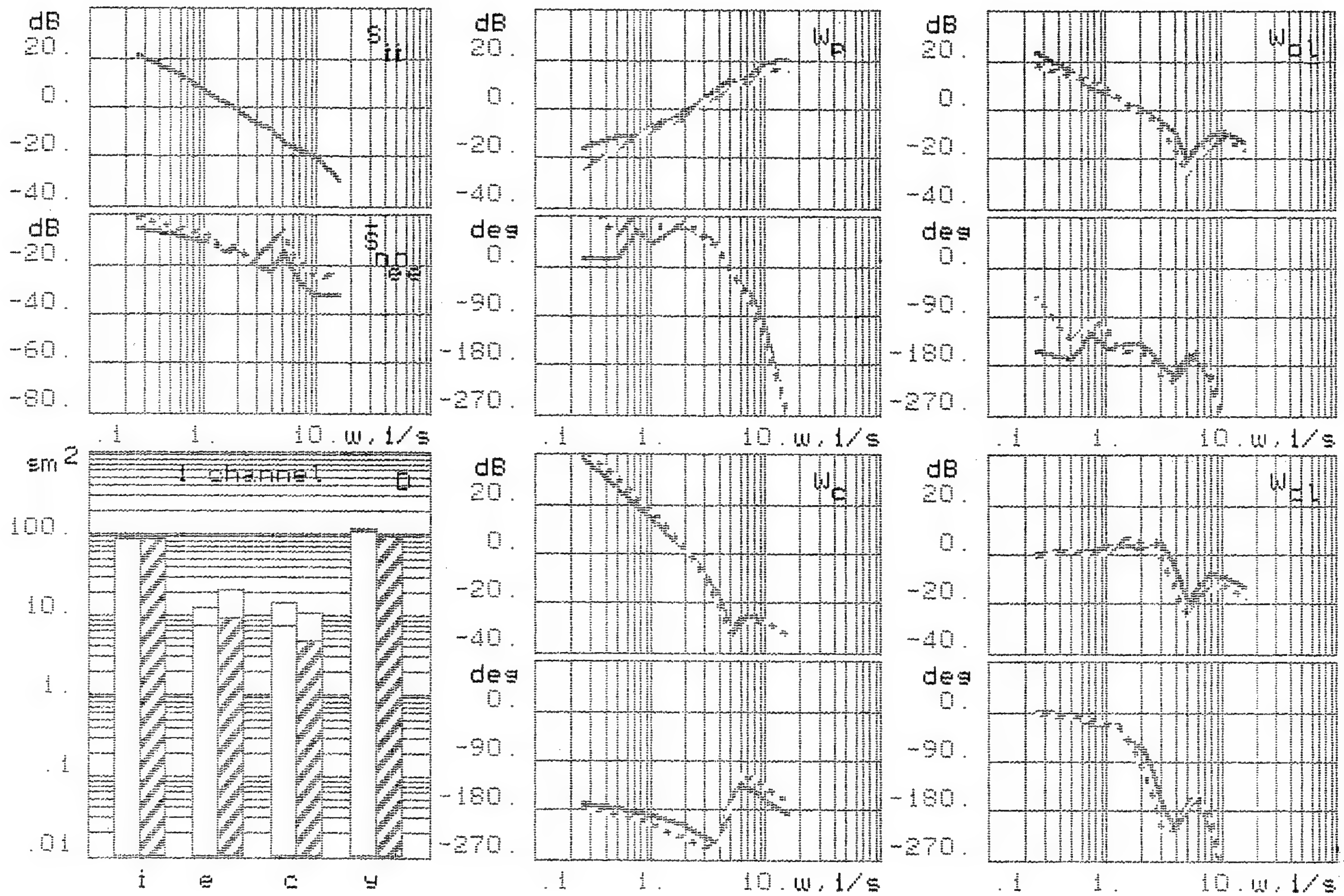


Fig.3.15. Influence of damping ratio ξ_{sp}

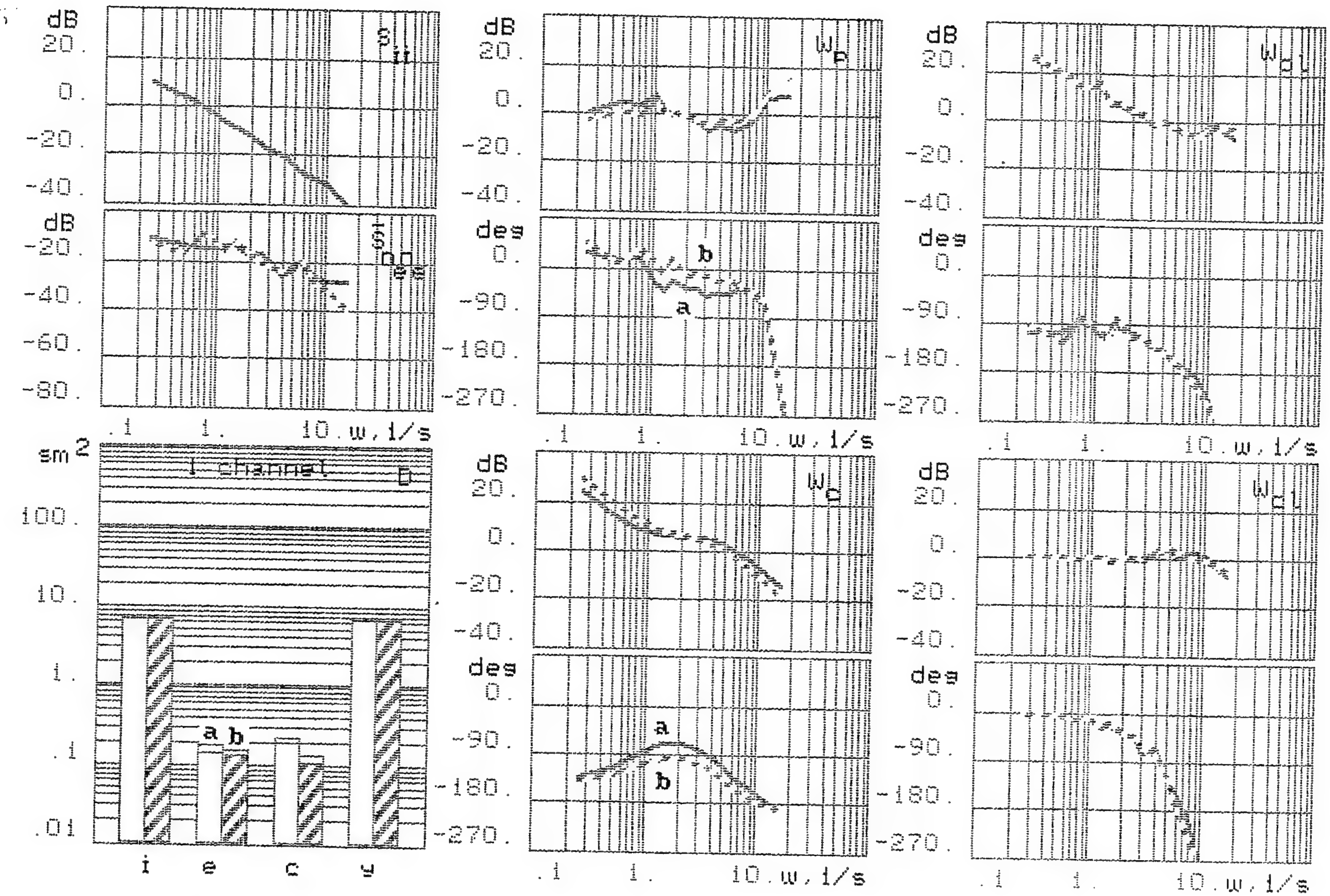


Fig.3.16. Influence of type of FCS (V/L = 0.5 1/sec)

a – conventional FCS

b – RCAH FCS

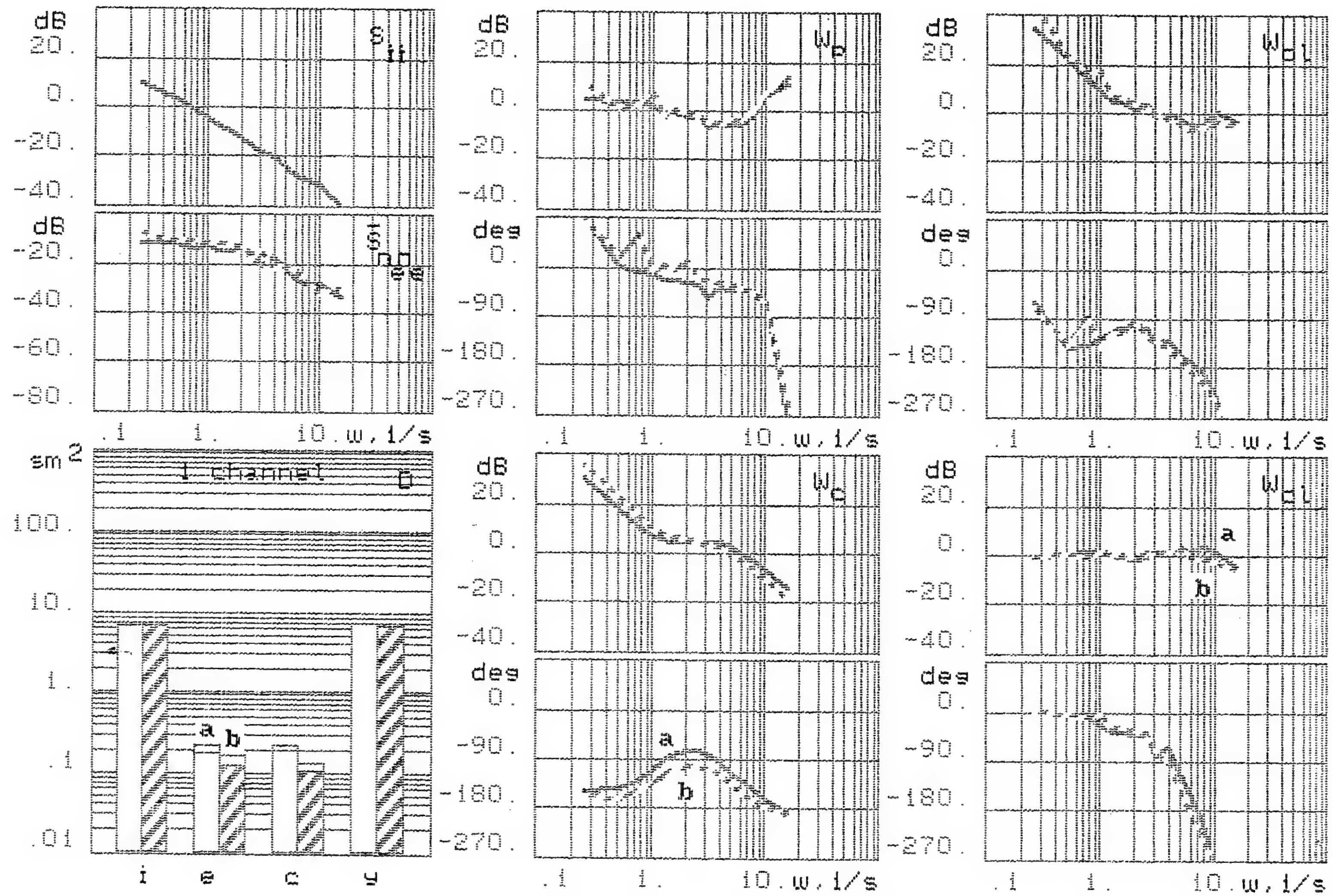


Fig.3.17. Influence of type of FCS (V/L = 1 1/sec)
a - conventional FCS
b - RCAH FCS

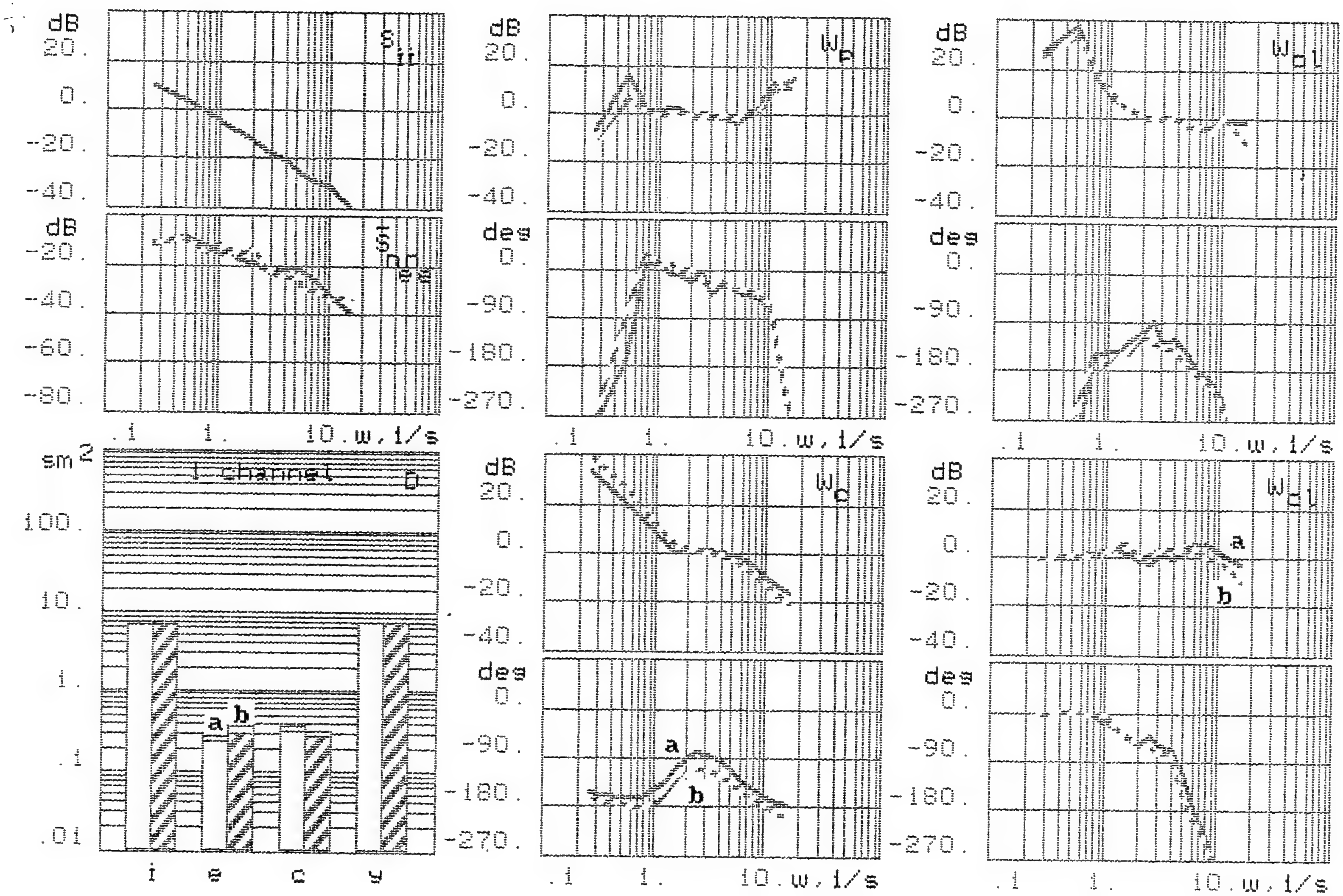


Fig.3.18. Influence of type of FCS (V/L = 2 1/sec)
a - conventional FCS
b - RCAH FCS

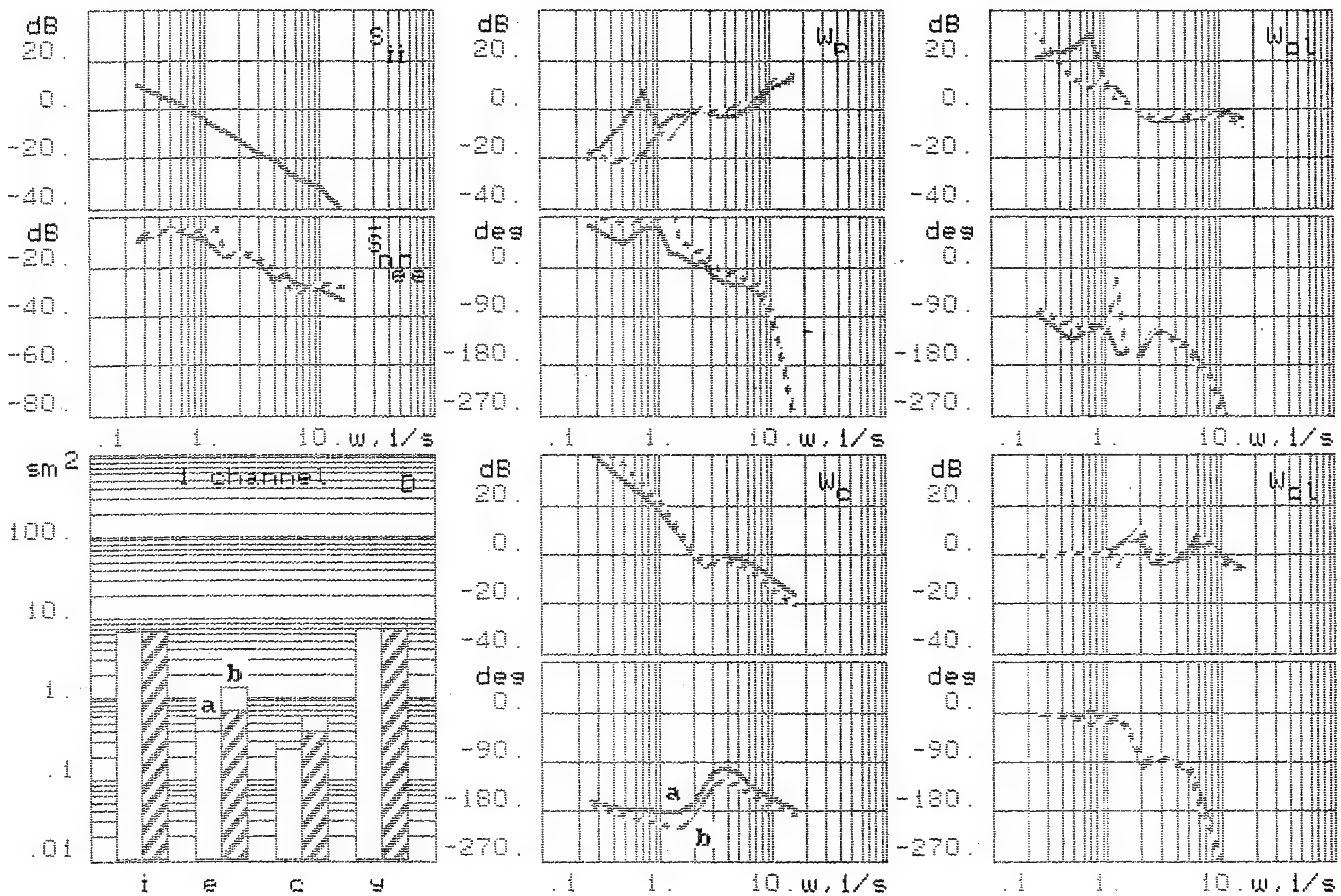


Fig.3.19. Influence of type of FCS (V/L = 5 1/sec)
a - conventional FCS
b - RCAH FCS

Acase type of FCS. The installation of prefilter $W_{pr} = \frac{Ts}{Ts+1}$ transformed the aircraft response in ACAH type of response leads to considerable inprovement in accuracy at low distances L. The experiments fulfilled in conditions of constant variance of input signal ($\sigma_i^2 \neq$ f(L)) demonstrated that effect from installation of prefilter W_{pr} depends on the type of system had the aircraft before the installation (RCAH or conventional). If the initional dynamics configuratin corresponded to RCAH type of response ($1/T_q > -Z_w$) than the addition of prefilter leads to increase of variance of error only on 10 % when parameter V/L increased from 1 up to 5 1/sec.

The considerably higher effect was achieved when this filter was installed in FCS on aircraft with mitical conventional response $1/T_q = -Z_w$. The experiments fulfilled in conditions simular above ($\sigma_i^2 \neq$ f(L)) the increase of parameter V/L from 1 up to 10 caused the decrease of variance of error up to 30 %. In that case the accuracy was reached in 4 times (for V/L = 5 1/sec) and 6 - 8 times (for V/L = 10 1/sec) higher in comperison with aircraft with prefilter (see fig.3.20 and 3.8). The ACAH type of system is accompanied by considerable decrease of lead compensation, and high frequency resonanse peak of closed loop system. As for low frequency resonanse peak it appears only when V/L ≥ 10 1/sec.

The results of experiments fulfilled for conditions when the percieved input was correlated with the distance L are shown in table 3.7a.

Table 3.7a

System	$V/l^* = 50$ 1/s	$V/l^* = 5$ 1/s
	σ_e^2/σ_i^2	σ_e^2/σ_i^2
Conventional	0.08	0.29
ACAH	0.14	0.04

There is seen from this table that effect of ACAH system is the same in sense of decrease of σ_e^2/σ_i^2 at small distance l^*. As for high distance (L = 50 m) the convenional type of response supplies the higher accuracy in comparison with ACAH type.

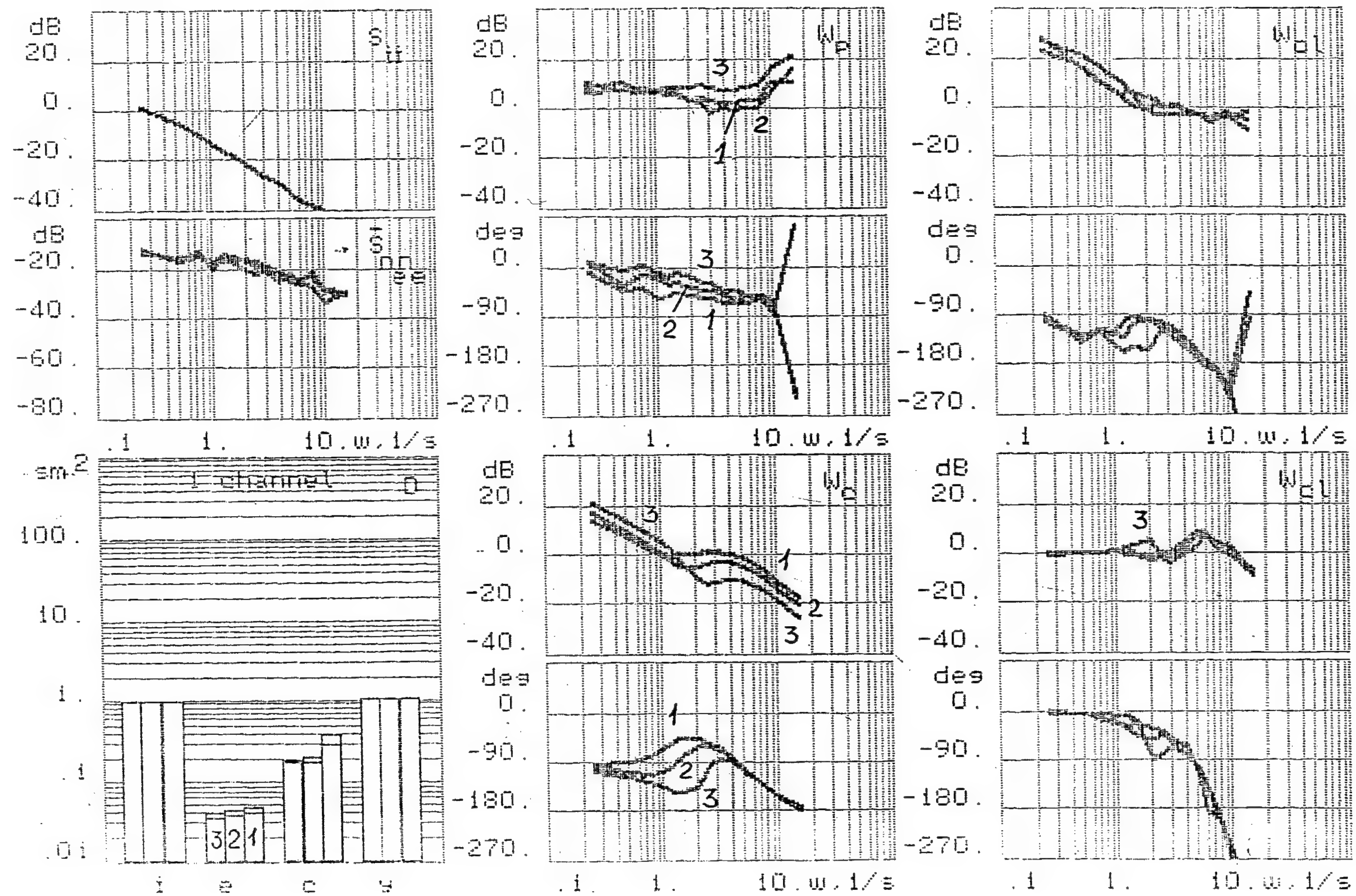


Fig.3.20. The influence of the distance (V/l^*) in longitudinal channel for ACAH system ($1/T_q > -Z_w$)

1. $V/l^* = 1$, 1/s; 2. $V/l^* = 2$, 1/s; 3. $V/l^* = 5$ 1/s

In case when ACAH type of response is realized by the pitch feedback there is neccesary to increase feedback gain coefficient (K_θ) considerably (K_θ = 8 ÷ 10) to get reasonable effect in decrease of variance of error. Nevertheless the accuracy achieved in that case is in 2 times (for (V/L = 5 1/s) and in 4 times (for V/L = 10 1/s) lower in comparison with the results obtained with ACAH type of system realyzed by the prefilter W_{pr}. All discussed effects are correct qualitevely for the experiments when except the longidutional channel pilot has to minimize the error in lateral channel too. The influence of increase number of channels will be discussed below.

b. The lateral channel

The results discussed below were obtained for case when pilot used aileron for control and simultaneously carried out the task in longitudinal channel. The variance of input signal σ_i^2 was chosen constanst to expose the influence of flight control system. There were compared the types of FCS (see table 3.3) supplied the conventional type of response without any feedbacks, with roll feedback ($\varphi \rightarrow \delta_a$), and finally the system supplied ACAH type of response by the prefilter $W_{pr} = \frac{0.5s}{0.5s+1}$.

The influence of a distance L had the same tendency as in longitudinal channel. The increase of parameter V/L from 2 up do 10 caused the increase of variance of variance of error up to 4 times (see fig.3.21). There is only one resonance peak in closed-loop system taking place at crossover frequency. The value of this peak increases on 4 ÷ 5 dB when parameter V/L increases from 2 up to 10 1/sec.

The influenses of FCS. The described above results were obtained for conventional configuration without any feedbacks and prefilters. Because of high order of aircraft dynamic pilot lead compensation was very high and the variance of error was close to variance of input signal (for V/L = 2 - 5) or even higher it (for V/L = 10).

The usage of bank angle as a feedback signal and prefilter $W_{pr} = \frac{0.5p}{0.5p+1}$ was accompanied by considerable decrease of variance of error. The variance σ_e^2 decreases in 2 times when only the feedback $\varphi \rightarrow \delta_a$ was used and in 3 times more when the prefilter was added to such FCS. Except in the range V/L = 2 - 5 1/s the variances of error staies practically didn't change.

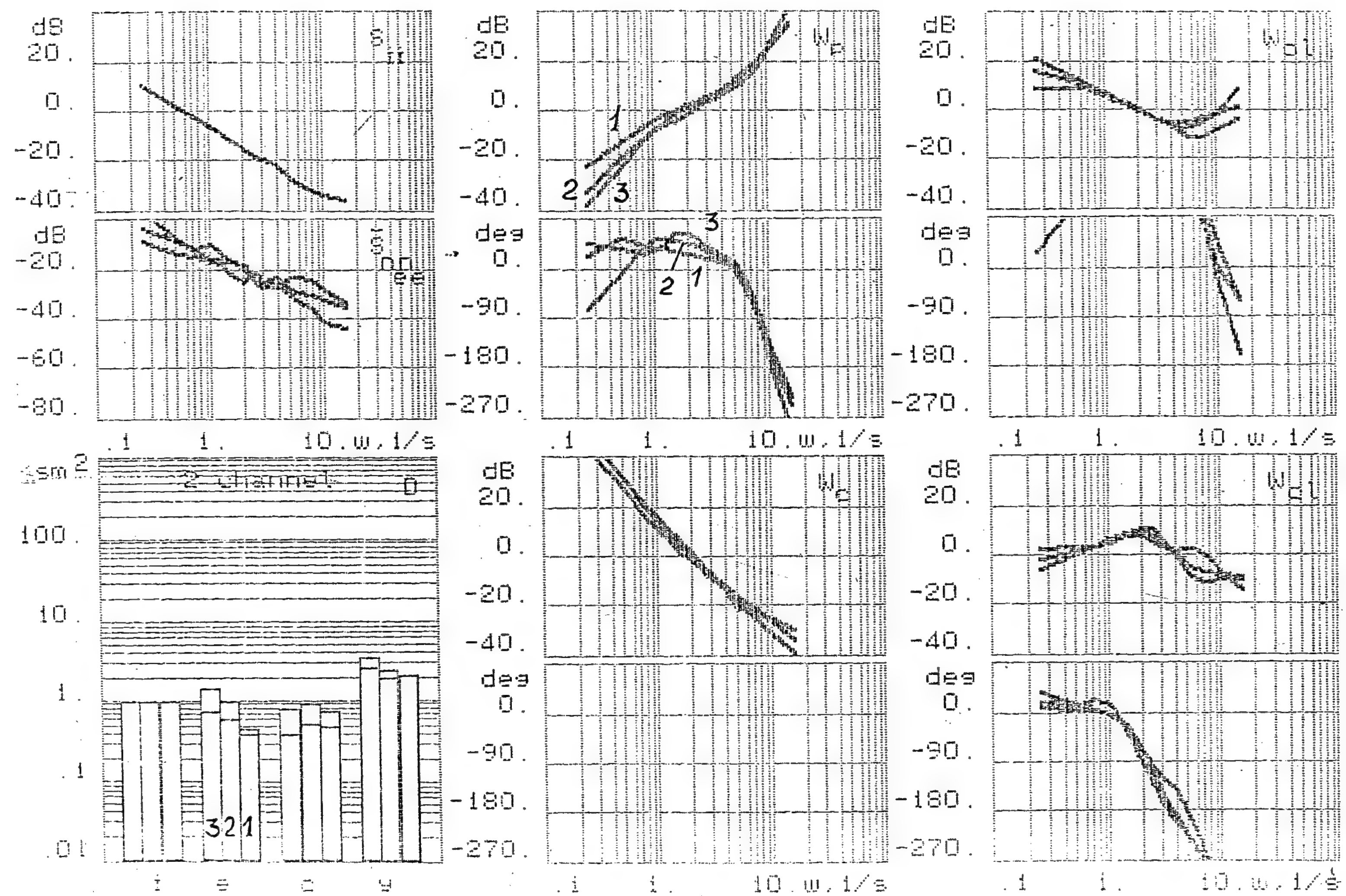


Fig.3.21. Influence of the distance (V / l^*) on pilot-vehicle system characteristics in lateral channel

1. $V / l^* = 2$ 1/s; 2. $V / l^* = 5$ 1/s; 3. $V / l^* = 10$ 1/s

The influence of longitudinal and lateral channel. The investigations demonstrated that the improvement of aircraft dynamics in one of the channel leads to the improvements of pilot-vehicle systems in other channel too. For example the installation of the prefilter W_{pr} realized the ACAH type of response in lateral channel leads to decrease of variance of error in lateral channel up to 25 % (see fig.3.22). The same effect takes place in lateral channel in case of improvement of aircraft dynamics in longitudinal channel. This results was obtained and by use optimal control modelling of pilot-vehicle system (see chapter 4).

In comparison with the single loop the increase of number of channels leads to increase of resonance peak in the main loop level of remnant and pilot rating. The influence of considered variable on the pilot rating can be evaluated with help of equation given in [18] and slightly modified in [14]

$$PR_m = A + \frac{1}{B^{m-1}} \prod_{i=1}^{m} (PR_i - A)$$

where A = 9; B = 8.3;

PR_i - pilot rating in "i" channel,

PR - general pilot rating, when pilot carries out control in m channels.

The analysis of equation demonstrated that the pilot ratings of flying qualities in channel one (PR^1) and channel two (PR^2), supplied the first and second levels has to be less 3.5 and 6.5 correspondingly. Only in this case the general rating PR_m can correspond to the first or second levels.

c. Nonstationary conditions

The experiments fulfilled in nonstationary conditions L=L(t) were carried out for the different variances of basket's desplacement on both coordinates ($\sigma^2_{H_B}$, $\sigma^2_{y_B}$ = 0; 0.01 m^2; 0.04 m^2; 0.09 m^2; 0.16 m^2; 0.64 m^2) with or without prefilter W_{pr} (in lateral channel $W_{pr} = \frac{0.5s}{0.5s+1}$; in longitudinal channel $W_{pr} = \frac{0.2s}{0.2s+1}$), for different

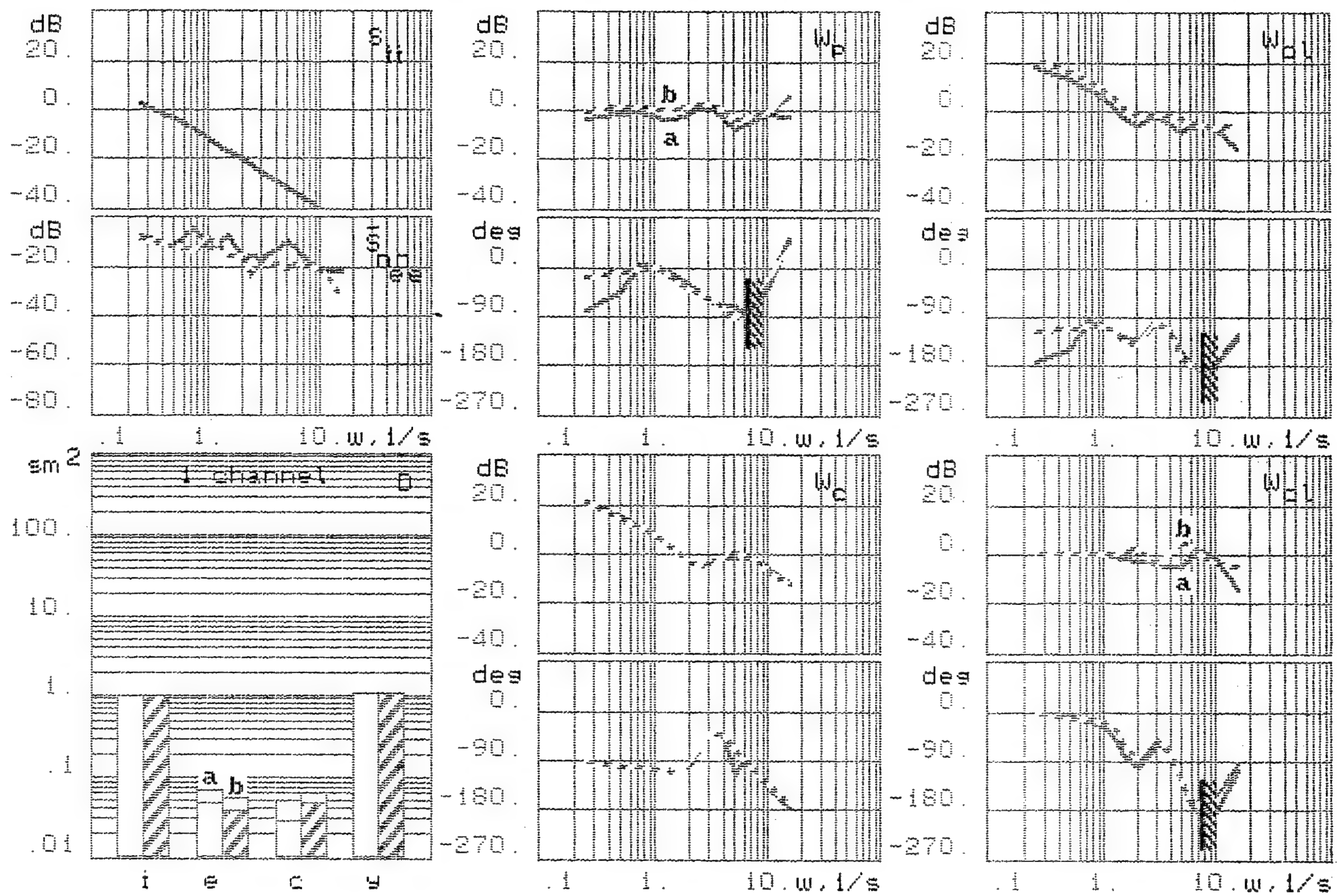


Fig.3.22. Influence of improvement in lateral channel on characteristics in longitudinal channel
a – $W_{pr} = 1$ in lateral channel
b – $W_{pr} = (0.5s)/(0.5s+1)$ in lateral channel

controlled element gain coefficient, for singleloop (longitudinal) and dual-channel system. The basic dynamic configuration in longitudinal channel corresponded to conf 2D (see table 3.10), in lateral channel it corresponded to configuration given in table 3.10.

Table 3.10

longitudinal channel | lateral channel

K	$-Z_W$	$1/T_q$	ξ_{sp}	ω_{sp}	T_1	l_p	$-\bar{M}_q$	a_0	T_2	K_φ
100 m/s	1.25 1.25	1.25 3.5	0.7 (1.4)	4.9	10 0.2	0	5	1°, 4°	10 1	0 1

$T_{1,2}$ are constants

of prefilters $W_{pr_{1,2}} = \dfrac{T_{1,2}s}{T_{1,2}s+1}$

K_φ - bank feedback gain coefficient

The results of experiments - final error (the error at the position of contact between probe and droque and probability on fulfilled of the task are given in tables 3.8 for a number of serieses of experiments.

First series of experiments

1. $\sigma_i = 0$, m

without prefilters in both channels

Table 3.11

№	1	2	3	4	5	6	7	8	9	10	average error, m
$K_{c1} = 0.1$ $K_{c2} = 0.1$	0.07	0.04	0.024	0.043	0.033	0.106	0.13	0.036	0.096	0.11	0.0588
$K_{c1} = 0.2$ $K_{c2} = 0.2$	0.06	0.053	0.038	0.044	0.032	0.1	0.08	0.16	0.137	0.06	0.071
$K_{c1} = 0.4$ $K_{c2} = 0.4$	0.367	0.192	0.405	0.273	0.214	0.382	0.225	0.46	0.14	0.064	0.272

with prefilters

Table 3.12

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c1} = 0.2$ $K_{c2} = 0.2$	0.153	0.0086	0.0428	0.026	0.045	0.026	0.015	0.015	0.01	0.033	0.03735
$K_{c1} = 0.4$ $K_{c2} = 0.4$	0.014	0.04	0.02	0.05	0.017	0.006	0.023	0.035	0.0037	0.023	0.0265
$K_{c1} = 0.6$ $K_{c2} = 0.6$	0.09	0.03	0.07	0.025	0.066	0.004	0.077	0.095	0.005	0.014	0.0476
$K_{c1} = 0.8$ $K_{c2} = 0.8$	0.08	0.19	0.013	0.063	0.056	0.2	0.024	0.13	0.057	0.11	0.0923

2. $\sigma_i = 0.2$, m

without prefilters

Table 3.13

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c1} = 0.2$ $K_{c2} = 0.2$	0.142	0.28	0.138	0.05	0.042	0.142	0.267	0.157	0.095	0.026	0.134
$K_{c1} = 0.4$ $K_{c2} = 0.4$	0.071	0.203	0.192	0.12	0.14	0.289	0.055	0.26	0.096	0.087	0.1512

with prefilters

Table 3.14

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c1} = 0.2$ $K_{c2} = 0.2$	0.077	0.066	0.065	0.08	0.063	0.068	0.083	0.063	0.0425	0.025	0.0631
$K_{c1} = 0.4$ $K_{c2} = 0.4$	0.032	0.074	0.0475	0.108	0.07	0.033	0.0726	0.028	0.0276	0.026	0.0517
$K_{c1} = 0.6$ $K_{c2} = 0.6$	0.047	0.08	0.113	0.123	0.09	0.078	0.25	0.16	0.148	0.1	0.119

3. $\sigma_i = 0.4$, m

without prefilters (gains $K_{c_{1,2}}$ were chosen by pilot)

Table 3.15

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c_1} = 0.2$ $K_{c_2} = 0.2$	0.196	0.5	0.393	0.153	0.36	0.56	0.75	1.0	0.7	0.08	0.46
$K_{c_1} = 0.4$ $K_{c_2} = 0.4$	0.37	0.252	0.145	0.171	0.065	0.464	0.102	0.534	0.466	0.42	0.365

with prefilters (gains $K_{c_{1,2}}$ were chosen by pilot)

Table 3.16

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c_1} = 0.4$ $K_{c_2} = 0.4$	0.1	0.16	0.13	0.116	0.246	0.291	0.146	0.18	0.042	0.132	0.154

4. $\sigma_i = 0.8$, m

without prefilters (gains $K_{c_{1,2}}$ were chosen by pilot)

Table 3.17

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c_1} = 0.4$ $K_{c_2} = 0.4$	1.65	17.73	1.29	6..3	0.8358	8.3	1.51	0.77	1.29	3.15	4.18

with prefilters (gains $K_{c_{1,2}}$ were chosen by pilot)

Table 3.18

№	1	2	3	4	5	6	7	8	9	10	average error,m
$K_{c_1} = 0.8$ $K_{c_2} = 0.8$	0.097	0.24	0.075	0.57	0.274	0.14	0.236	0.29	0.245	0.22	0.2387

Second series of experiments

a) $\sigma_i = 0.1$, m

without prefilters W_{pr} in both channels $K_c = 0.05$ Table 3.19

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.09	0.125	0.11	0.14	0.003	0.01	0.07	0.03	0.14	0.015	0.0733

with prefilters $K_c = 0.01$ Table 3.20

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.05	0.07	0.06	0.03	0.035	0.05	0.014	0.03	0.04	0.03	0.0369

b) $\sigma_i = 0.2$, m

without prefilters $K_c = 0.01$ Table 3.21

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.1	0.29	0.08	0.25	0.076	0.27	0.12	0.245	0.18	0.28	0.179

with prefilters $K_c = 0.15$ Table 3.22

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.077	0.045	0.07	0.04	0.01	0.03	0.03	0.06	0.08	0.05	0.0492

c) $\sigma_i = 0.3$, m

without prefilters $K_c = 0.15$ Table 3.23

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.01	0.035	0.6	0.7	0.2	0.47	0.17	0.19	0.86	0.29	0.3525

with prefilters $K_c = 0.2$ Table 3.24

№	1	2	3	4	5	6	7	8	9	10	average error, m
e	0.084	0.09	0.05	0.11	0.05	0.08	0.09	0.071	0.063	0.074	0.0772

d) $\sigma_i = 0.4$, m

without prefilters $K_c = 0.2$ Table 3.25

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.23	0.17	0.3	0.26	0.37	0.12	1.2	0.2	0.38	0.26	0.348

with prefilters $K_c = 0.25$ Table 3.26

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.036	0.037	0.2	0.03	0.04	0.16	0.07	0.016	0.14	0.05	0.078

e) $\sigma_i = 0.6$, m

without prefilters $K_c = 0.3$ Table 3.27

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.33	2.36	0.88	6.3	1.916	0.64	0.27	0.82	1.18	0.06	1.175

with prefilters $K_c = 0.3$ Table 3.28

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.073	0.09	0.22	0.11	0.013	0.009	0.16	0.03	0.08	0.17	0.0855

Third series of experiments

a) $\sigma_i = 0.1$, m

without prefilters $K_c = 0.1$ Table 3.29

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.103	0.03	0.003	0.008	0.02	0.067	0.057	0.05	0.014	0.02	0.0372

with prefilters $K_c = 0.1$ Table 3.30

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.06	0.05	0.03	0.028	0.04	0.035	0.036	0.005	0.027	0.04	0.0351

b) $\sigma_i = 0.2$, m

without prefilters $K_c = 0.1$ Table 3.31

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.16	0.13	0.2	0.18	0.19	0.01	0.09	0.14	0.26	0.18	0.154

with prefilters $K_c = 0.1$ Table 3.32

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.13	0.07	0.003	0.11	0.075	0.03	0.02	0.05	0.036	0.002	0.0526

c) $\sigma_i = 0.4$, m

without prefilters $K_c = 0.2$ Table 3.33

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.25	0.37	0.016	0.24	0.09	0.11	0.13	1.15	0.08	0.01	0.2455

with prefilters $K_c = 0.25$ Table 3.34

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.06	0.11	0.05	0.12	0.09	0.1	0.1	0.06	0.07	0.06	0.08

d) $\sigma_i = 0.6$, m

without prefilters $K_c = 0.3$ Table 3.35

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	1.51	0.025	0.95	0.45	0.415	0.14	0.06	0.23	0.62	0.34	0.474

with prefilters $K_c = 0.3$ Table 3.36

№	1	2	3	4	5	6	7	8	9	10	average error,m
e	0.17	0.07	0.21	0.05	0.09	0.06	0.07	0.1	0.1	0.13	0.104

The experiments in unstationary conditions

(only longitudinal channel)

1) $\sigma_i = 0.1$, m

without prefilters Table 3.37

№	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.056	0.036	0.056	0.07	0.069	0.092	0.012	0.017	0.0	0.06	0.083	0.024	0.072	0.034	0.014	0.0425

with prefilters

Table 3.38

№	1		3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.052	0.044	0.032	0.074	0.016	0.06	0.015	0.015	0.018	0.074	0.034	0.058	0.012	0.025	0.018	0.036

2) σ_i = 0.2 mra-

without prefilters

Table 3.39

№	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.038	0.047	0.026	0.015	0.089	0.025	0.031	0.02	0.011	0.05	0.063	0.033	0.01	0.053	0.042	0.055

with prefilters

Table 3.40

№	1		3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.02	0.024	0.03	0.073	0.026	0.035	0.09	0.01	0.05	0.02	0.028	0.045	0.053	0.006	0.063	0.038

3) σ_i = 0.4m

without prefilters

Table 3.41

№	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.058	0.2	0.095	0.022	0.146	0.195	0.079	0.02	0.09	0.023	0.015	0.01	0.08	0.017	0.29	0.1305

with prefilters

Table 3.42

№	1		3	4	5	6	7	8	9	10	11	12	13	14	15	average error,m
e	0.03	0.16	0.04	0.062	0.044	0.07	0.14	0.18	0.04	0.066	0.084	0.025	0.02	0.025	0.024	0.067

The influence of prefilters the experiments demonstrated the considerable improvements of measured characteristics for ACAH system in case of increased values of variance of basket's displacement (see fig.3.23).

The probability of successful fulfillment of refueling task for wide interval of variance of basket's displacement is considerably higher in case of use ACAH type of FCS (fig.3.24). The comparisons of final error obtained in experiments in singleloop (see fig.3.25) and dual loop system (fig.3.24) demonstrates that the main part of error is defined by the error in lateral channel.

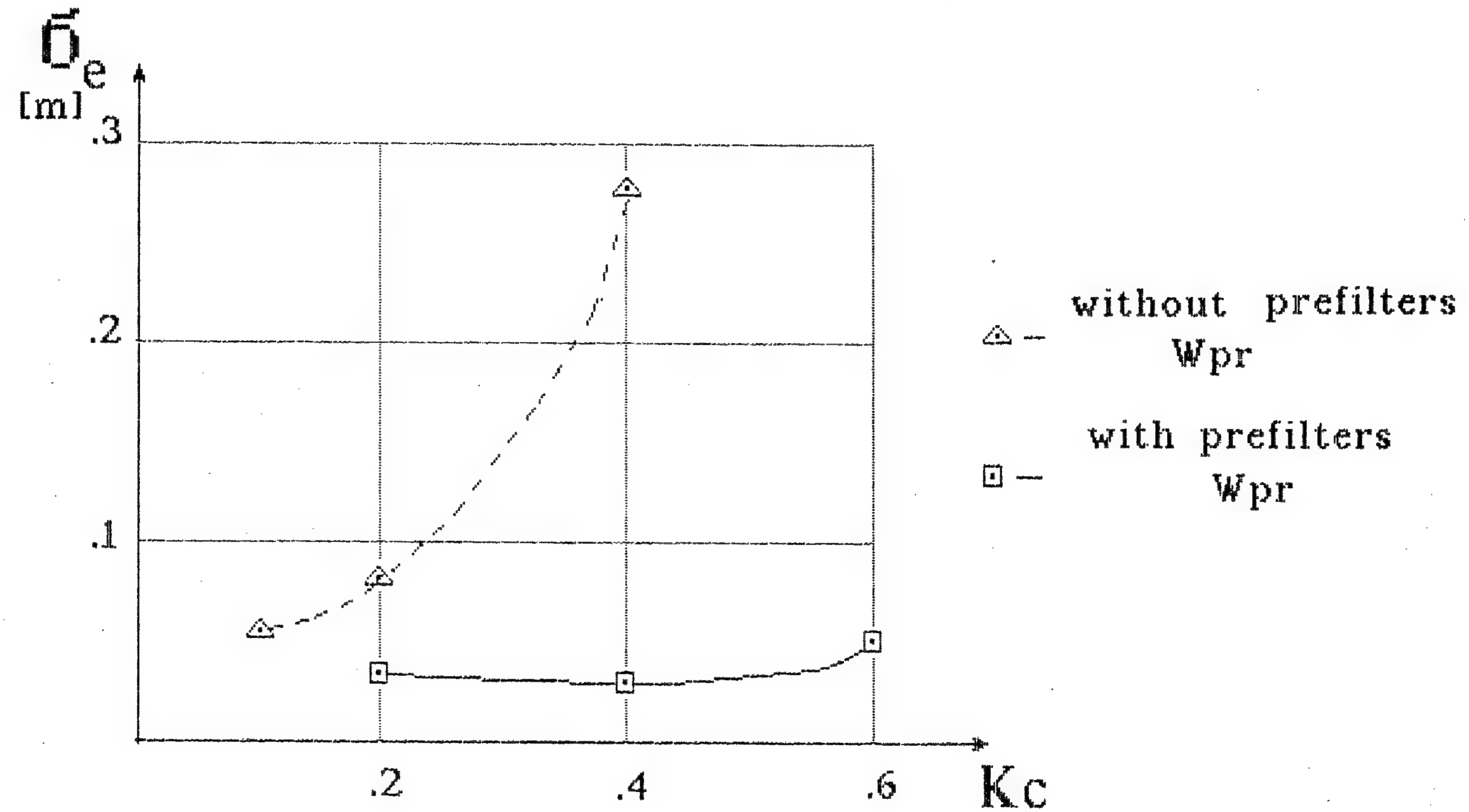


Fig.3.23. Influence of gain coefficient Kc on accuracy (dual channel case)

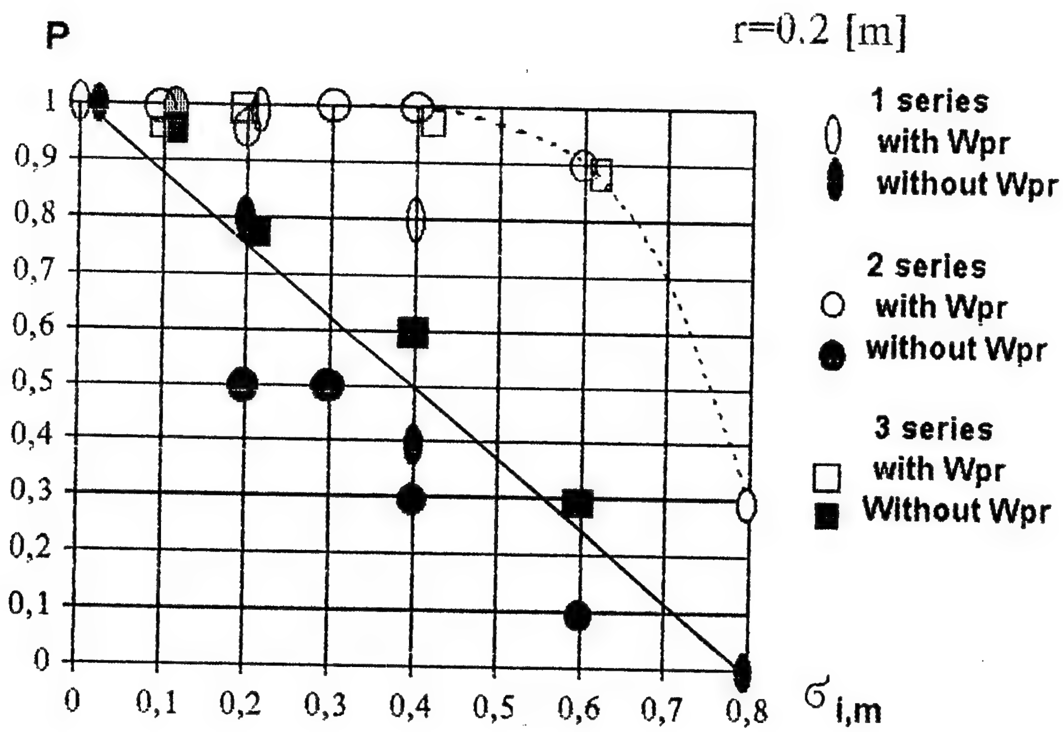


fig. 3.24. Probability of fulfilment of refueling task

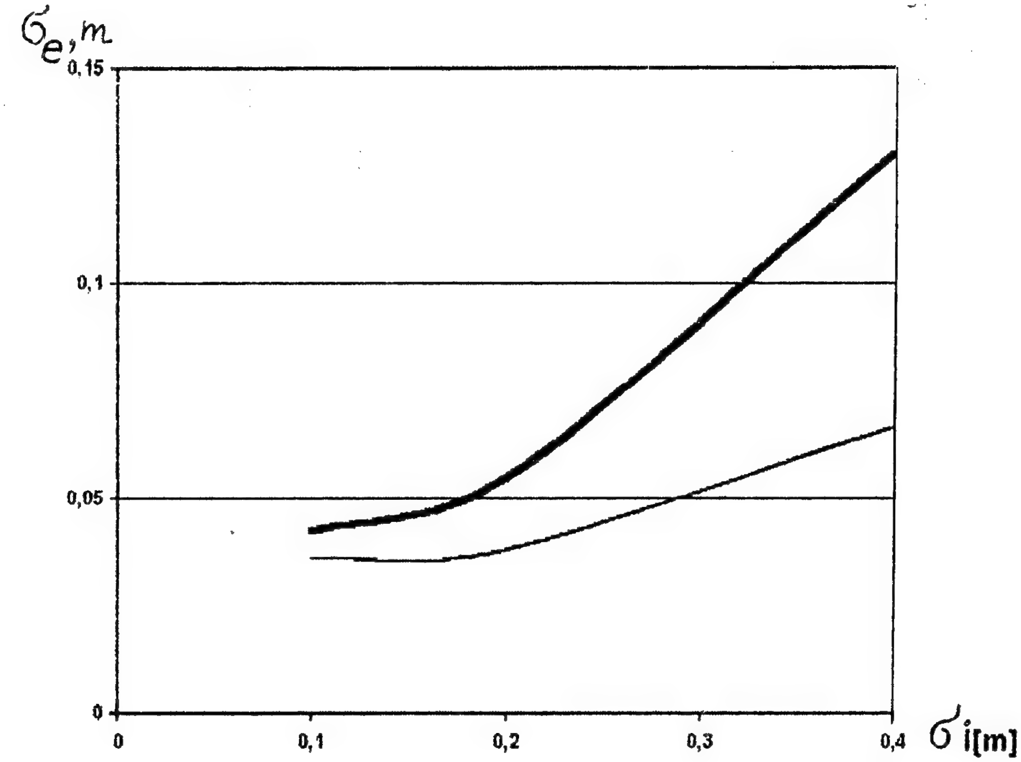


Fig.3.25. Influence of variance of input signal on accuracy single loop case

The increase of variance of input signal caused the increased of optimum gain coefficient. The optimum was defined in the first sevies of experiments as a value supplied the minimum of mean square error (fig.3.26) . In 2 and 3 series of experiment the gain coefficients were chosen when inrease..

3.3.2. The development of criteria for evaluation of flying qialities in refueling task

There were carried out the experiments on MAI workstation with dynamic configurations given in tables 3.4, 3.5 with goal to develop the criteria for evaluation of flying qualities in refueling task. The values of measured pilot-vehicle system characteristics are given in table 3.41.

The flying qualities were evaluated for the distance between pilot and droque equal to L = 5 m, and for distance between pilot and center of gravity equal l_p = 2 m. It means that parameter l^* = 7 m. The controlled element dynamics in this conditions close to the dynamics $W_c = \frac{\varepsilon L(s)}{\alpha(s)} \frac{\Delta H}{\alpha(s)}$ and at the same time the pilot's workload and achieved errors allowed to differ investigated configurations in case of use Cooper-Harper scale.

The pilot task was the compensation of error between the center of droque and center of cross indicated the end of probe. The picture drown or the screen is shown on fig.3.27.

The altitude control tracking task is considerably more diffecult in comparison with the attitude tracking task. According to the technique described in chapter.2 this factor requires to change the ratio $\frac{d_{des}^{task}}{d_i}$. For the considered dynamic configurations this ratio was chosen equal to 0.5. This value allowed to get pilot ratings in rather wide range from PR = 2 up to PR = 7.

The desired performance was chosen equal to the a half of droque diameter (d): $d_{des}^{task} = \frac{1}{2}d$. For the distance L = 5 m and for d = 0.8 m d_{des}^{task} = 0.4 m or d_{des}^{task} ≅ 4.6 deg. In that case the mean square error of input σ_i = 2, 3 deg. The spectral density of input signal was defined by the second order model $S_{ii} = \frac{K^2}{(\omega^2 + 0.5^2)^2}$.

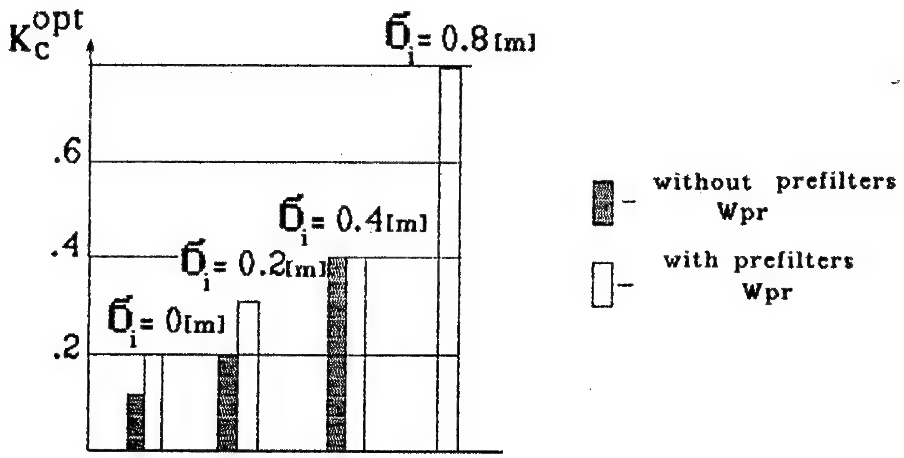


Fig. 3.26. Influence of input on optimal gain coefficient K_c^{opt} (dual channel case)

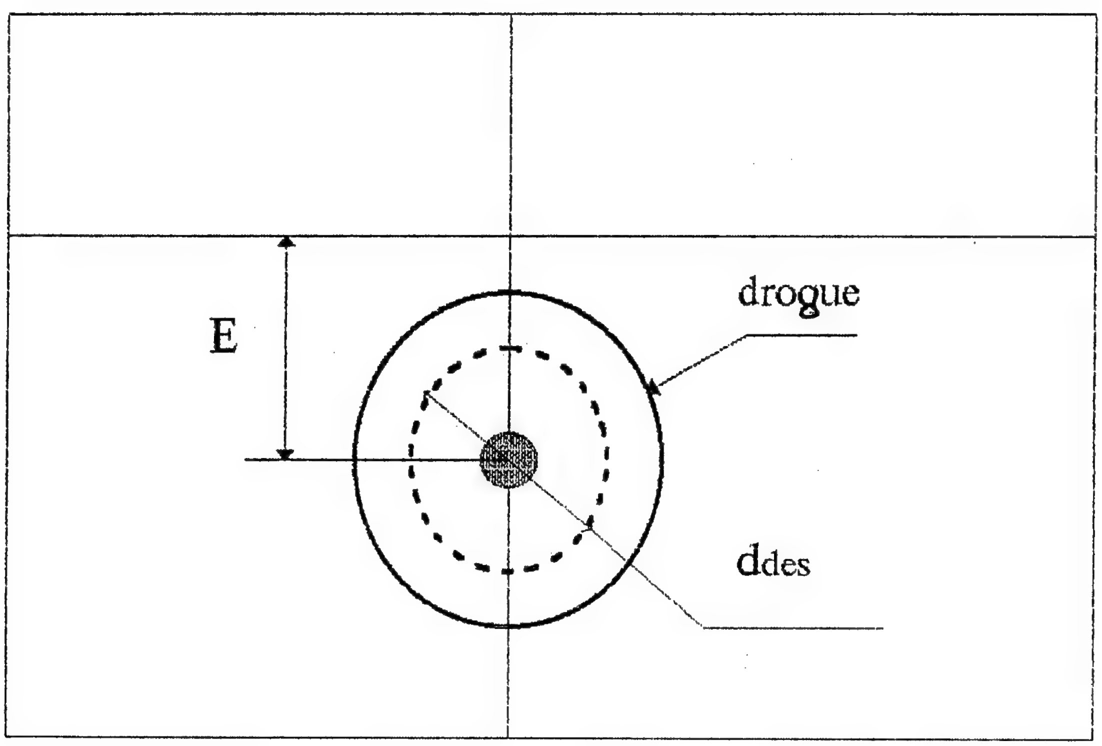
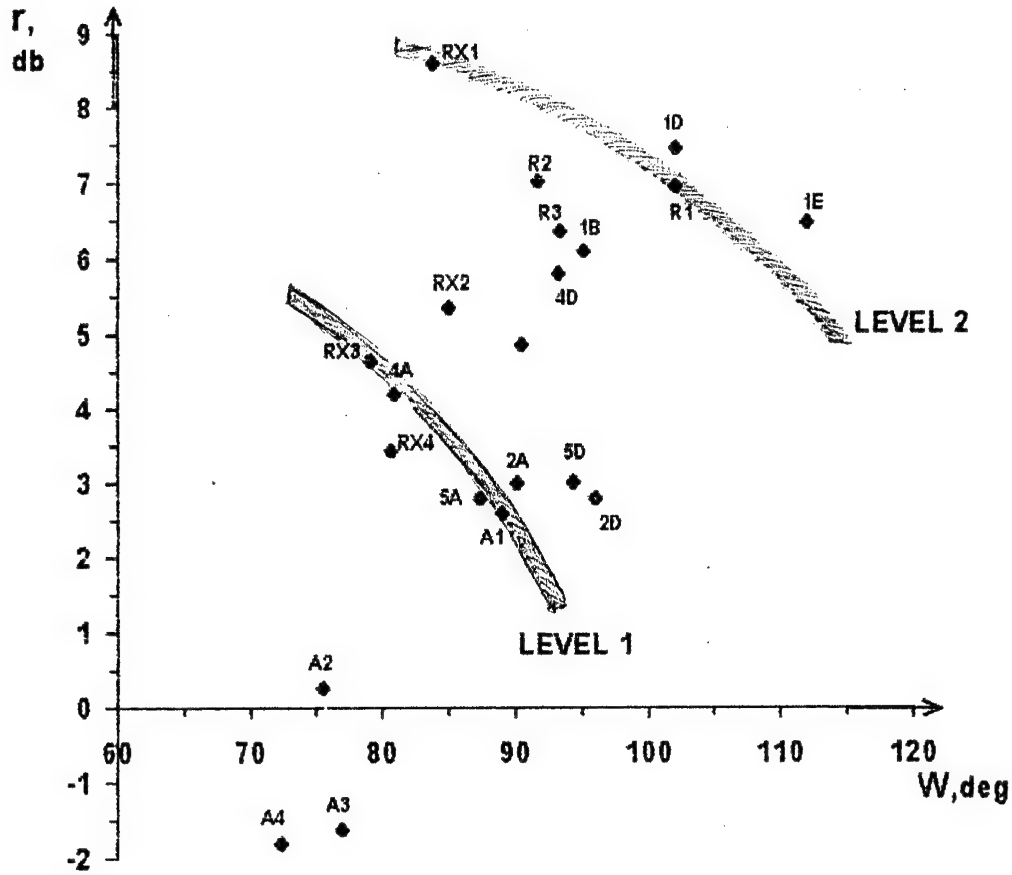


Fig.3.27. Display

The obtained values of normalized resonance peak ($\bar{r}$) in closed-loop system, pilot phase compansation ($\Delta\varphi_p$) calculated according to the rule given in chapter 3.1 allowed to get the lines of equal pilot ratings (PR = 3.5 and PR = 6.5) in the range $\bar{r}$, $\Delta\varphi_p$ fig.3.28 which can be considerable as a criteria for evalution of flying qualities in refueling task.



Pilot phase compensation

Fig.3.28. Criteria for evaluation of flying qualities in refueling task

conf	r,db	W,°	PR
1D	7.46	102	5÷6
2D	2.8	96	3
4A	4.2	80.9	2÷3
5A	2.8	87.3	2÷3
1B	6.1	95.1	4
2A	3	90.1	2÷3
1E	6.47	112	6÷8
4D	5.8	93.2	4÷5
5D	3.02	94.4	4÷5

conf	r,db	W,°	PR
R1	6.96	102	7
R2	7.02	91.7	7
R3	6.35	93.4	6
R4	4.87	90.4	5
RX1	8.6	83.7	7
RX2	5.35	85	6
RX3	4.65	79.1	5
RX4	3.44	80.6	3÷4

conf	r,db	W,°	PR
A1	2.61	89	4÷5
A2	.26	75.5	3÷4
A3	-1.6	75.8	2÷3
A4	-1.8	72.4	2÷3

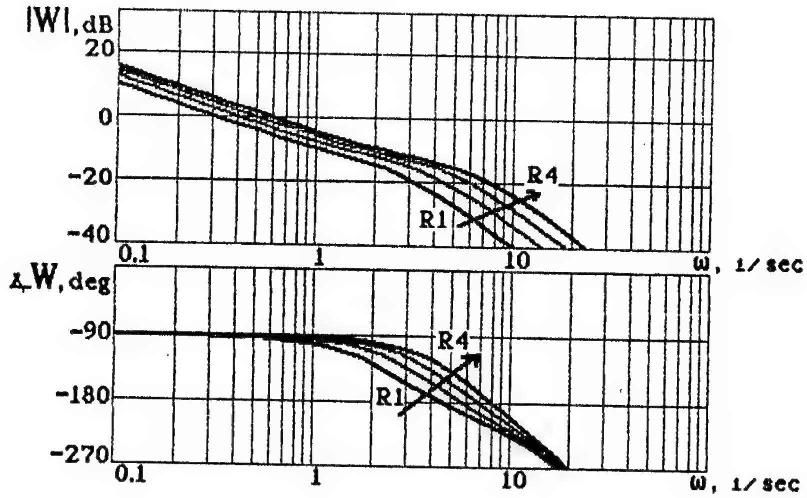


Fig.3.29. The frequency response characteristics of basic configurations $W_c^{\theta}(j\omega)$ for $W_{pr}=1$

CHAPTER 4

THE SOME MODIFICATIONS OF HUMAN-OPERATOR OPTIMAL CONTROL MODEL (OCM) AND ITS APPLICATION TO THE DIFFERENT MANUAL CONTROL TASKS

4.1. The modified OCM of human-operator behavior

The human-operator OCM had wide use in investigations of different manual control tasks. The structural scheme of OCM is shown on fig.4.1. The cost function used in majority research has the following form:

$$J = \sigma_e^2 + Q_{\dot{u}}\sigma_{\dot{u}}^2 .$$

Analysis of investigations demonstrates that the form of cost function doesn't allow:

- to get accurate results close to experimental in many cases;
- to define the optimal controlled element gain coefficient.

In [1] it was developed the modified algorimth for OCM where the cost function had the form

$$J = \sigma_e^2 + Q_u\sigma_u^2 + Q_{\dot{u}}\sigma_{\dot{u}}^2 . \tag{4.1}$$

It that case the careful choice of weighting coefficient Q_u allowed to improve the agreement between all modeling and measured frequency and integral characteristics.

Because of the considerable difference in obtained values of weighting coefficient Q_u ($Q = 0 \div 1.5$, see [1]) this version of OCM can be used only for analysis of results obtained in experiments. It makes doubtful to use this model for reliable prediction of results.

The developed in [1] version of OCM gives the different results for the different controlled element gain coefficient (K_c). In this model the influence of K_c is the same as the influence of weighting coefficient Q_u, because of in this case K_c is a scale factor for σ_u^2.The shortcoming of this modified model is also impossibility to expose the influence of K_c on component of variance of error uncorrelated with input signal ($\sigma_{e_n}^2$) and ratio $\frac{\sigma_{e_n}^2}{\sigma_e^2}$. At the same time the experiments (see fig.4.2)

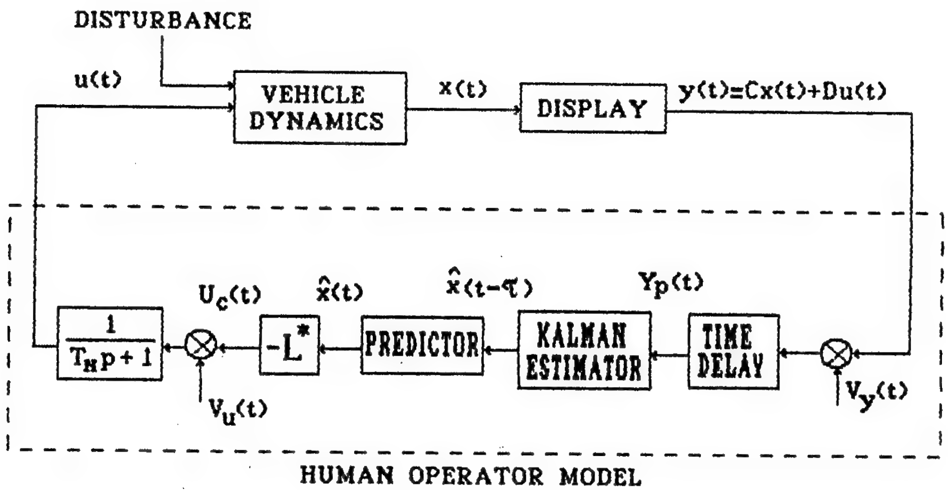


Fig.4.1. Structure of OCM

demonstrate such effect.

In the frame of current investigation the developed modifications allowed to predict the results of mathematical modeling with high reliability. There were carried out the following modifications

- the modified model of motor noise,
- the procedure for the choice of the model's parameters,
- the procedure for the optimization of controlled element gain coefficient.

The modified model of motor noise. It was offered the following model for the motor noise

$$V_{ua} = V_u^o + \rho_{ou}\sigma_{ua}^2 .$$

The introduction of the additive noise V_u^o allowed to increase the potentialities of model:

- to take into account the effect of increase the level of the noise in case of increase of controlled element gain coefficient,
- to decide the problem in choice of weighted coefficients in cost function.

The introduction of additive noise increases the level of total noise what requires to decrease the values ρ_{ou} and ρ_{yi}.

The procedure for the choice of ρ_{ou}, $\rho_{yi} \cdot \rho_{ou}$ and V_u discusses below together with the procedure for the choice of weighting coefficients in cost function.

The procedure for the choice of the model's parameters. The choice of OCM parameters with modified model of motor noise was based on experiments fulfilled for the different controlled element gain coefficient. For the choice it was used the simplified controlled element dynamics of aircraft (3.3) corresponding to the air-to-air tracking task with the following parameters: $-Z_W$ = 1.25 1/s, V = 250 m/s, L = 600 m, $\xi = 1$, $\omega = 2.5$ 1/s, $K_c = 0.5\,K_c^*$, K_c^*, $2\,K_c^{**}$ where K_c^* corresponded to the value chosen by pilot ($K_c^* = 2.262$ 1/deg).

The input signal has the spectral density

$$S_{ii} = \frac{K^2}{(\omega^2 + \omega_i^2)^2}, \ \omega_i = 0.5 \text{ 1/s}, \ \sigma_i^2 = 4 \text{ sm}^2.$$

The results of experiments shown on fig.4.2 demonstrate the obvious optimum $K_{c_{opt}}$ supplied the minimum variance of error. The procedure for the choice of parameter had the goal to define the OCM parameters supplied the agreement between calculated gain coefficient and $K_{c_{opt}}$ obtained experimentally. By direct comparison of the results it was obtained the parameters given in table 4.1.

Table 4.1.

T_N,s	τ, s	V_u^o	ρ_{oy_1}	ρ_{oy_2}	ρ_{ou_2}	Q_u 1/deg^2
0.05	0.25	0.02	0.005	0.005	0.003	0.01

The chosen parameters allowed to get the results of mathematical modeling. Show on fig.4.3 and fulfilled to the same (as in experiment) controlled element dynamics. There is seen good agreement between all measured and calculated characteristics. These OCM parameters were used for the following modeling of applied manual control tasks.

Procedure for optimization of controlled element gain coefficient. The existence of minimum variance of error in function $\sigma_e^2 = f(K_c)$ was used in development procedure in choice of $K_{c_{opt}}$. This procedure is carried out according to the criteria min σ_e^2 in parallel with the calculation of the pilot describing function fulfilled according to the cost function (4.1). In majority cases the predicted gain coefficient corresponded to optimal coefficient defined in following experiments.

It is shown below in analysis of pitch tracking tasks for HAVE PIO configurations.

4.2. The application of optimal control model of human-operator for the different manual control tasks

The modified optimal control model was applied for investigation of several piloting tasks: pitch tracking task for Have PIO configurations, air-to-air tracking task, refueling

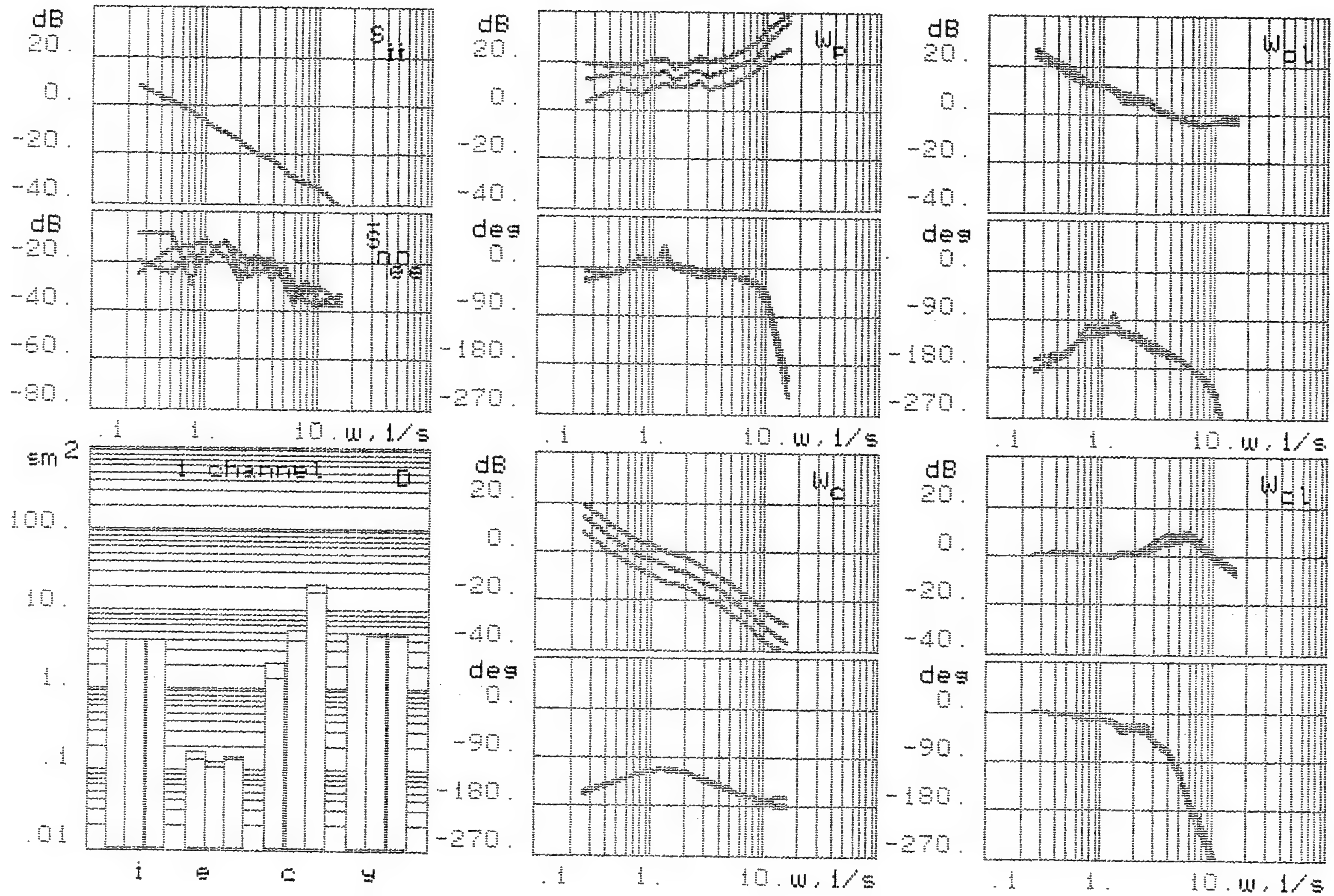


Fig.4.2. Experimental results for K_c=var

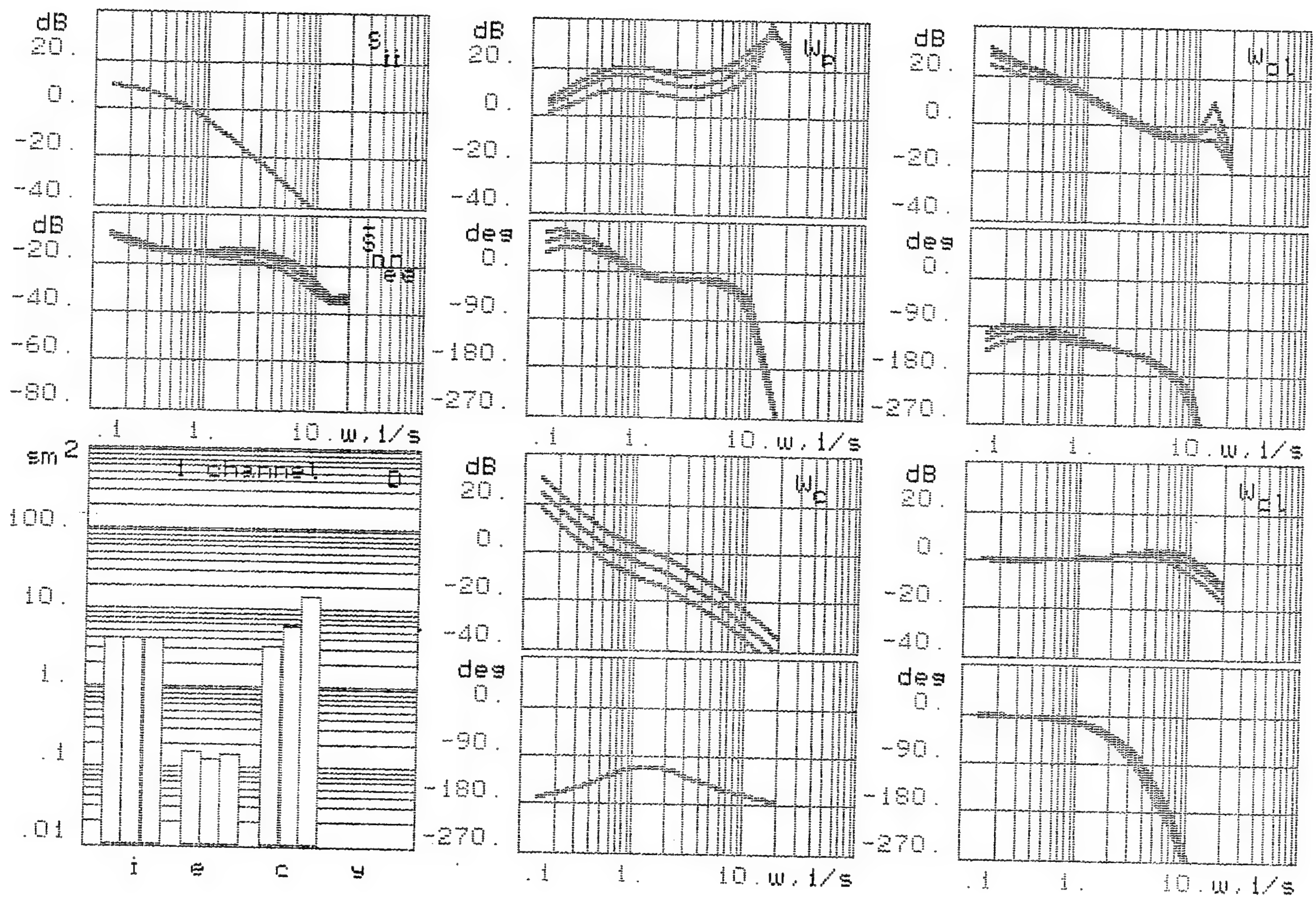


Fig.4.3. Mathematical modeling for K_c=var

task. The results of the mathematical modeling are discussed below.

a. The application of OCM model to pitch control tracking task with HAVE PIO configurations

The modified OCM was used for the modeling of pitch control tracking task with HAVE PIO data base.

The experiments with HAVE PIO configurations were fulfilled with one of the side stick having the different characteristics in comparison with the other side stick used for in described above experiments fulfilled for the choice of OCM parameters. Due to this circumstance it was determined the necessity to change the neuromuscular time lag. It was defined that the best value of this parameter corresponding to the used manipulator is $T_N = 0.2$ sec. The results of mathematical modeling demonstrated good agreement of with experiments for all investigated configurations on fig.4.4-4.18 there are given the results of such comparison and on fig.4.19-4.20 results of mathematical modeling only.

The mathematical modeling was carried out with controlled element gain coefficients chosen in experiments by pilot. Additionally at was calculated the optimal gain coefficient supplied the minimum variance of error with help of OCM.

The results of this additional modeling are given in table 4.2. There is seen that except configurations 2.5, 3.1 the OCM allowed to predict K_c very accurately (the maximum error in prediction of this coefficient was 60 % for configuration 2.5).

The results of the modeling and experimental investigation given in table 4.2 were used also and development of function $PR = f(\sigma_e^2)$. The function was obtained from equation (2.10) by supposing that

$$\frac{d}{d_{opt}} = \frac{\sigma_e}{\sigma_{opt}}$$

where for considered input signal $\sigma^2_{e_{opt}} = 0.0625 \text{ deg}^2$.

Taking it into account it was obtained

$$PR = 8.43 + 2.68 \ln \sigma_e^2 \tag{4.2}$$

On fig.4.21 there given the values PR and σ_e^2 obtained in experiments and by use the function (4.2) where variance σ_e^2 corresponded to calculated values. The results

Table 4.2

Config.	σ_e^2	K_c^{exp}	$K_{c_{opt}}$	PR^{exp}
2-B	0.192	1.5	1.7	3
2-1	0.246	1.5	(1.9-2.4)	4
2-5	0.468	2.5	4	6
2-7	0.339	3	_*)	5
2-8	0.363	1.75	_*)	5
3-D	0.201	2.25	2	4
3-1	0.195	3	1.8	4
3-3	0.270	-	2.5	-
3-6	0.246	2.5	_*)	5
3-8	0.297	2.75	_*)	5
3-12	0.538	3	3.5	6.5
3-13	0.451	2.5	2.5	5
4-1	0.212	1.75	1.75	3
4-2	0.268	-	2	-
5-1	0.279	2.5	(3.25-3.5)	5
5-9	0.474	3.5	(3.0-3.5)	5
5-10	0.570	3	(3.0-3.5)	6.5

* - no data because of long time duration of calculation.

demonstrated that the function can be used for the prediction pilot rating. In average it gives increased value of PR on 0.5 unit.

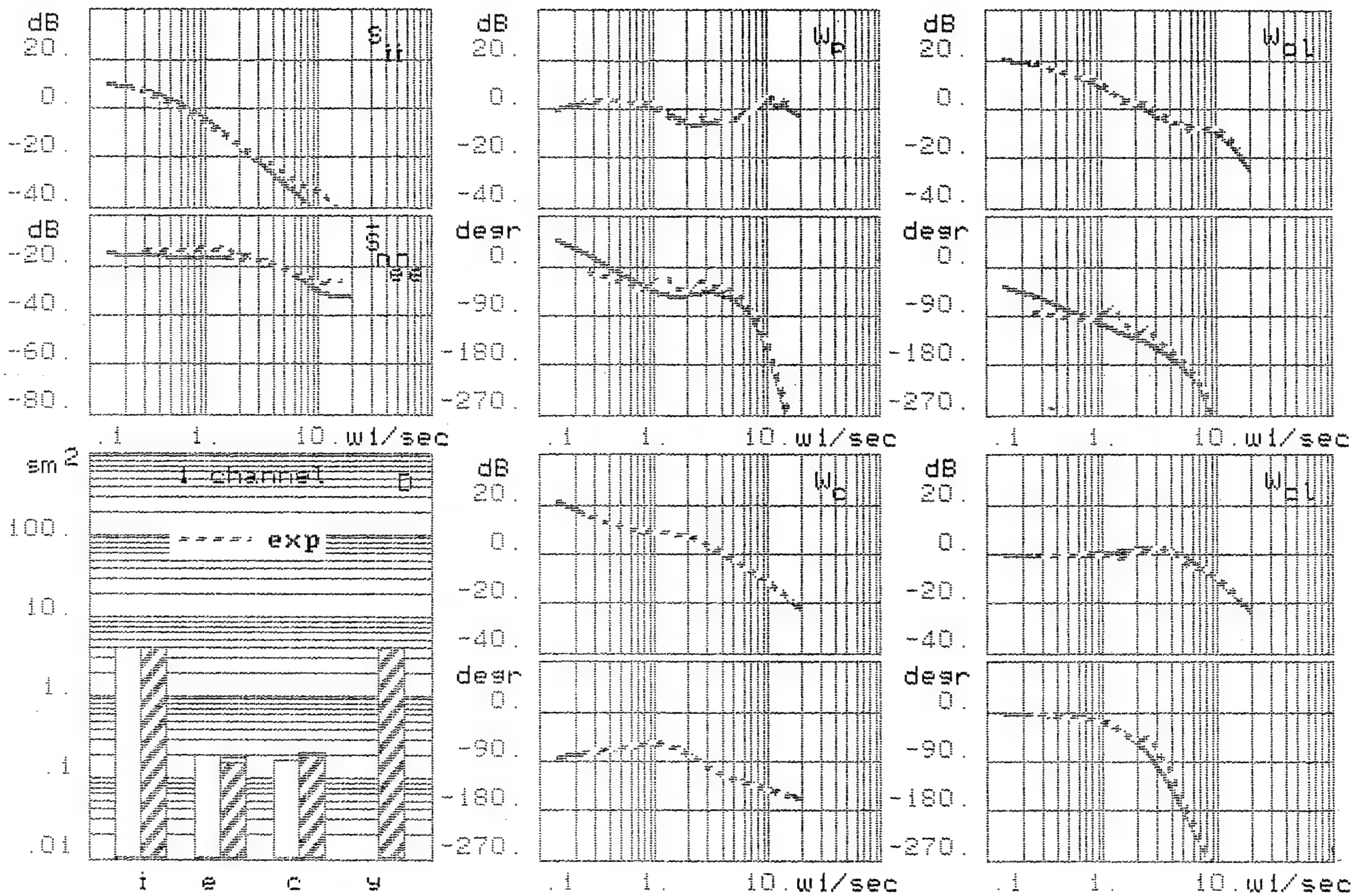


Fig.4.4. Comparison of mathematical modeling and experimental results (conf. 2-B)

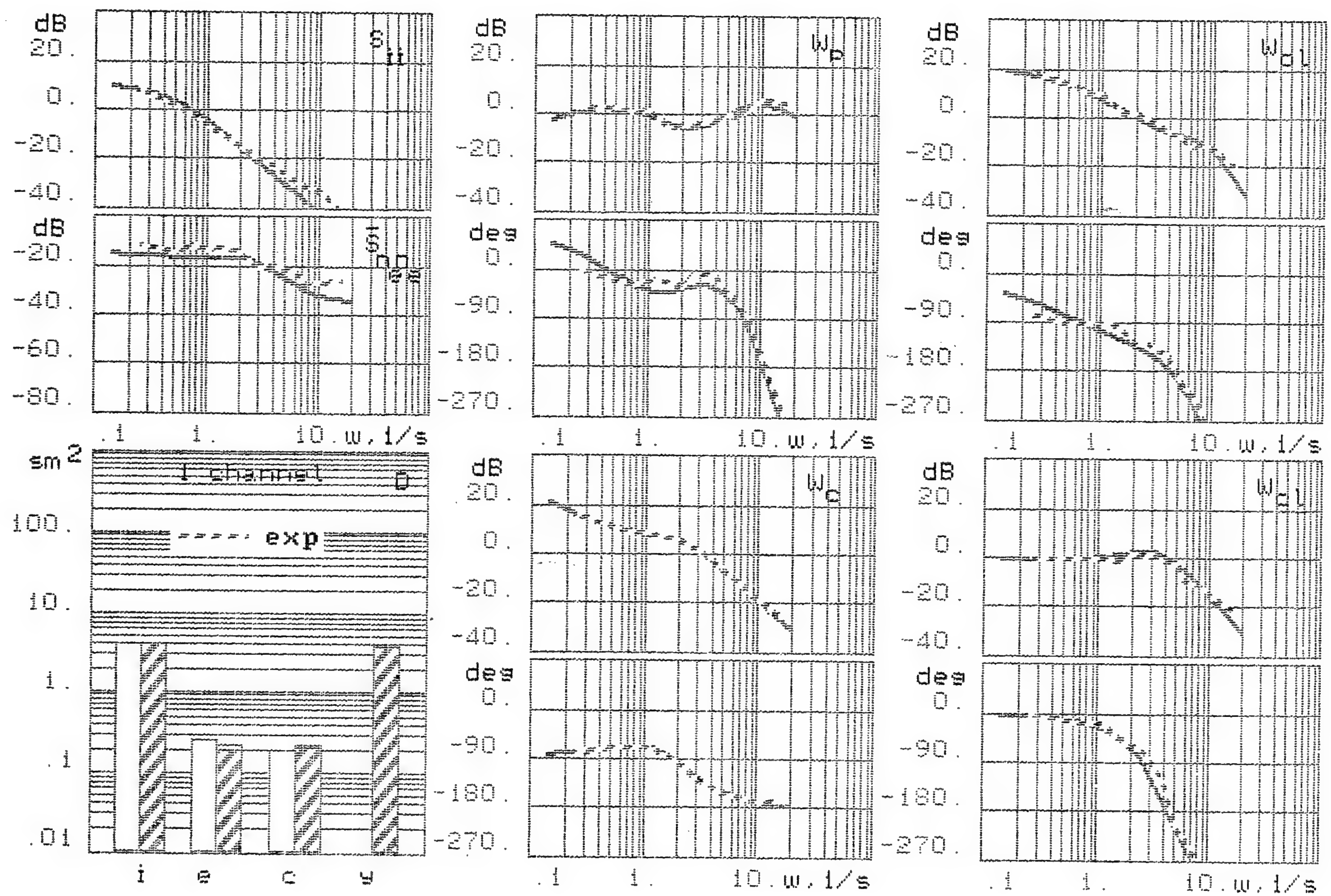


Fig.4.5. Comparison of mathematical modeling and experimental results (conf. 2-1)

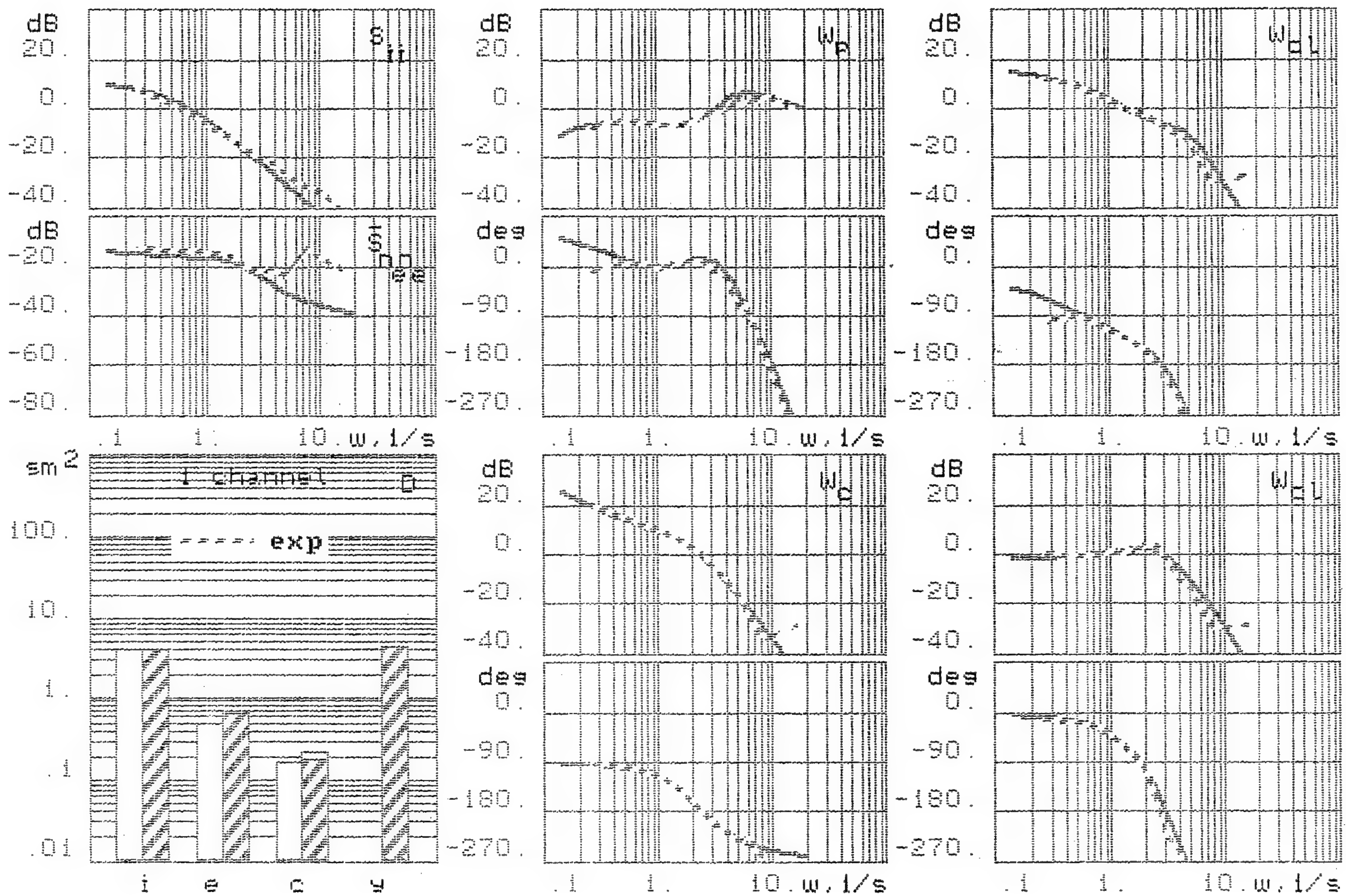


Fig.4.6. Comparison of mathematical modeling and experimental results (conf. 2-5)

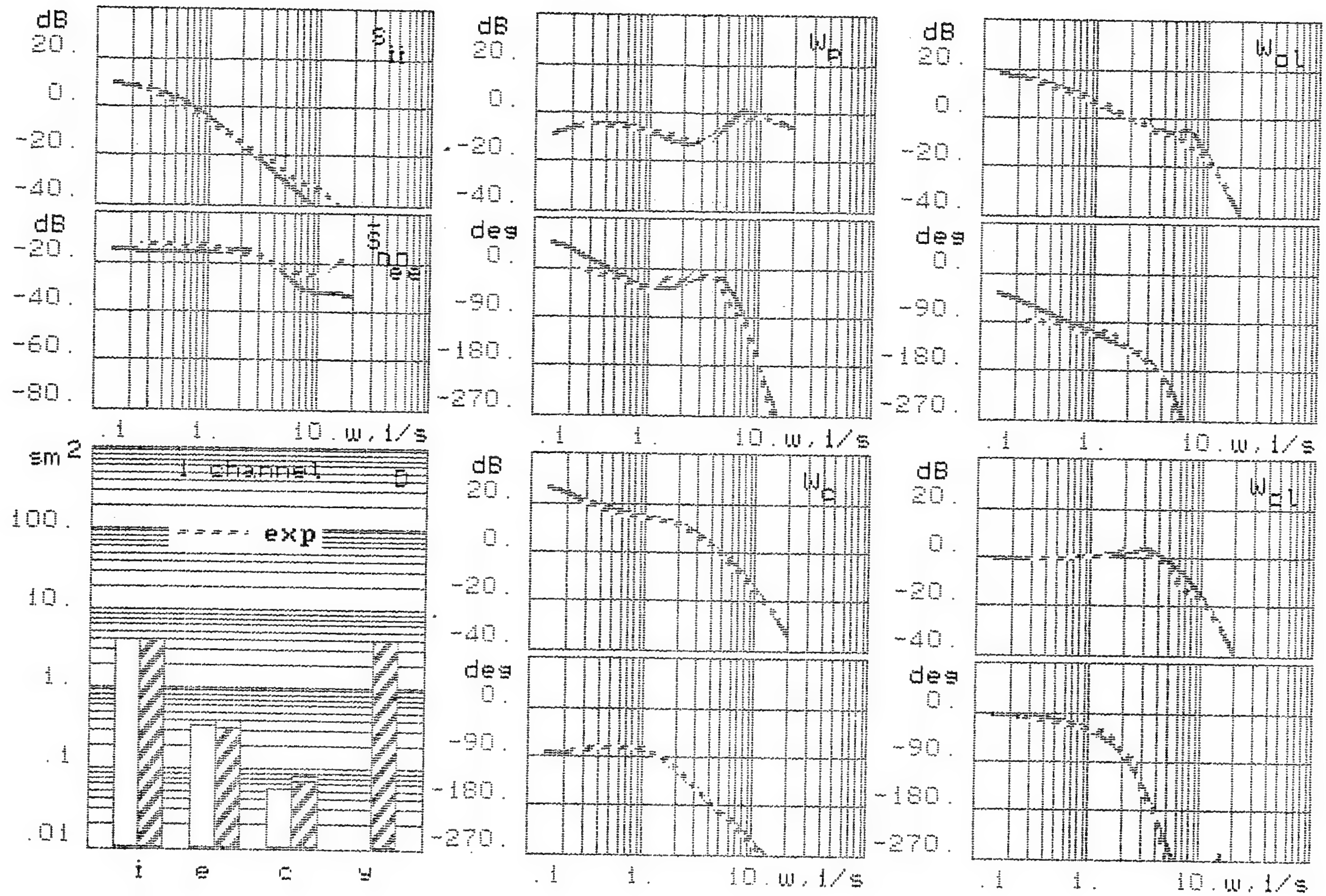


Fig.4.7. Comparison of mathematical modeling and experimental results (conf. 2-7)

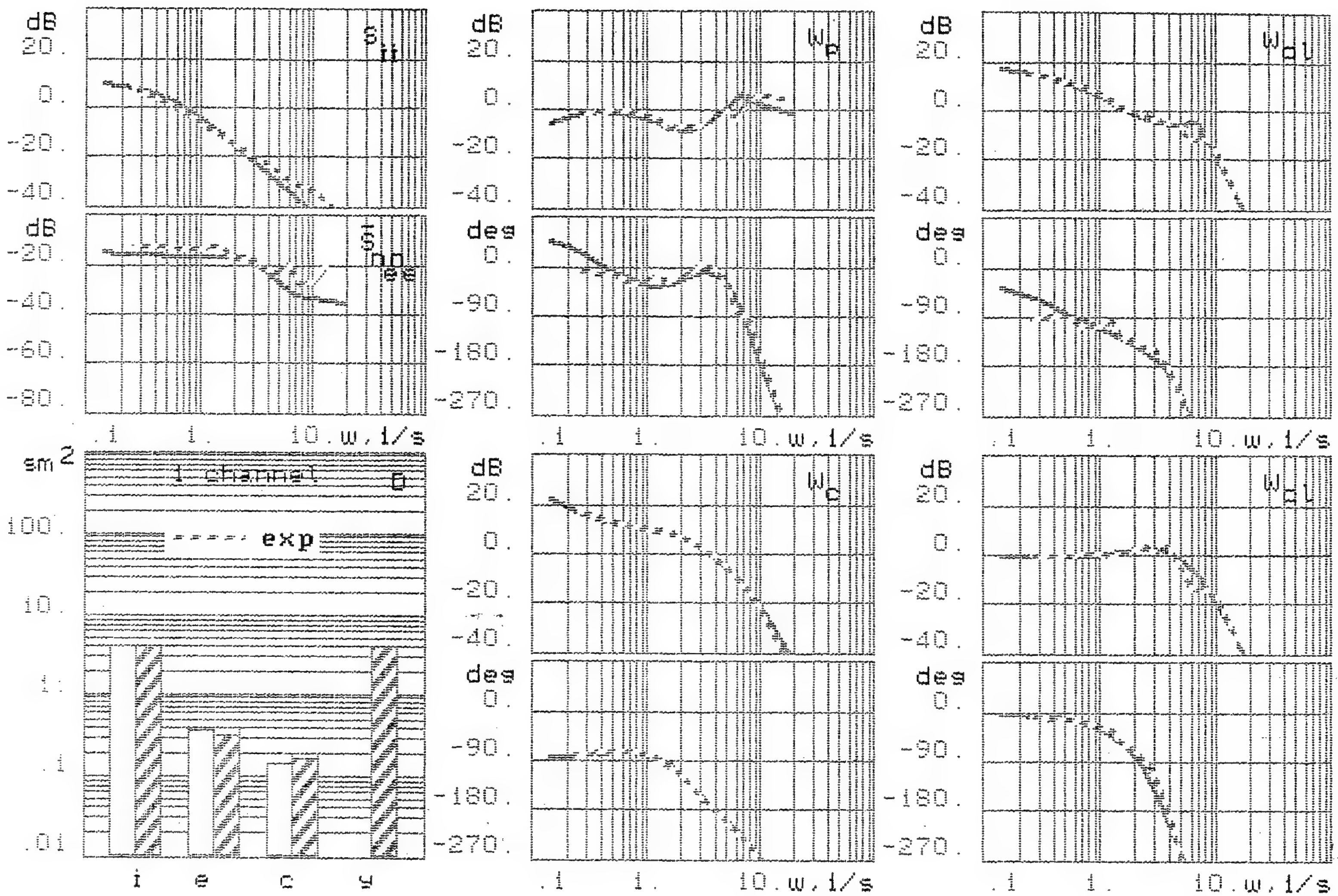


Fig.4.8. Comparison of mathematical modeling and experimental results (conf. 2-8)

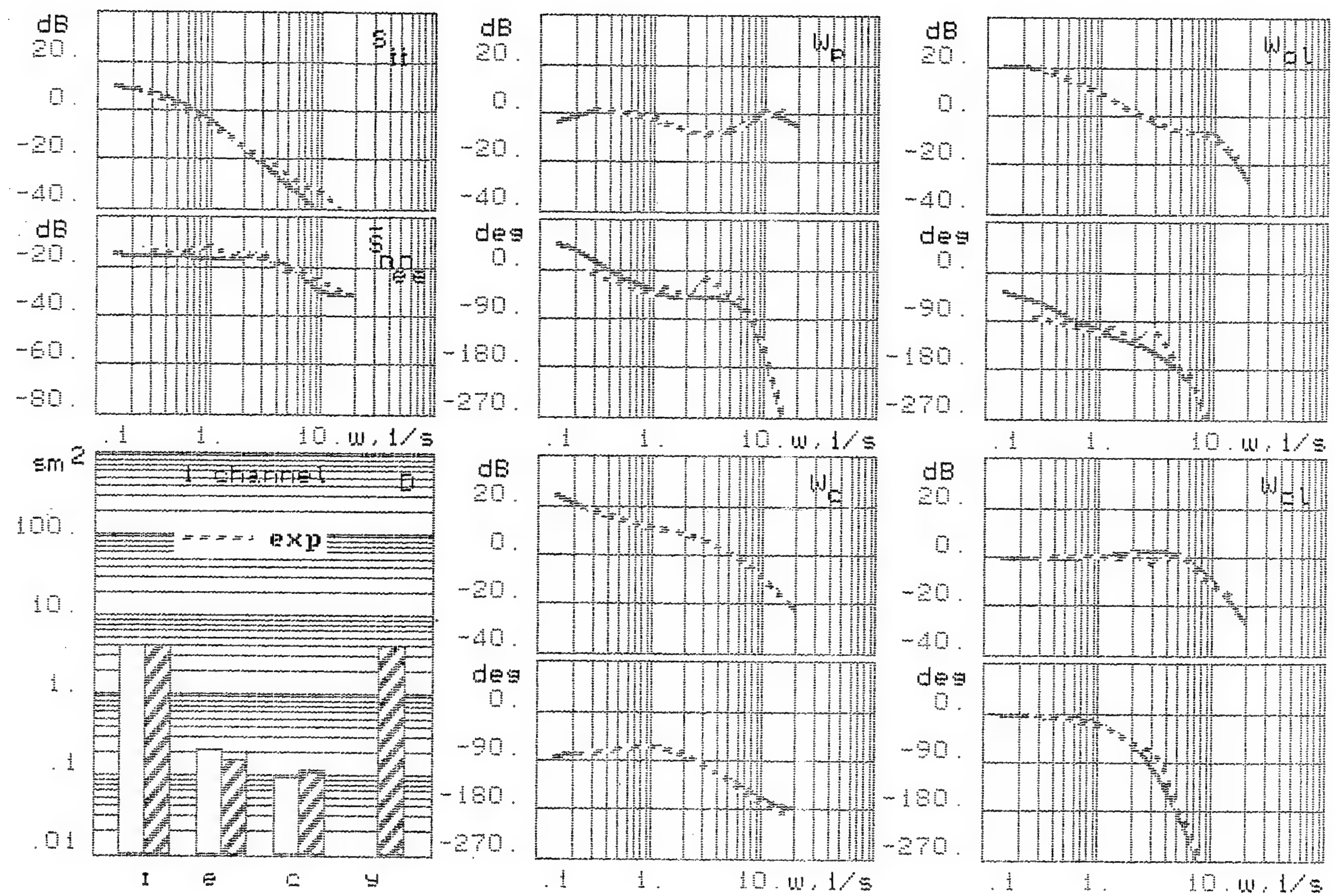


Fig.4.9. Comparison of mathematical modeling and experimental results (conf. 3-D)

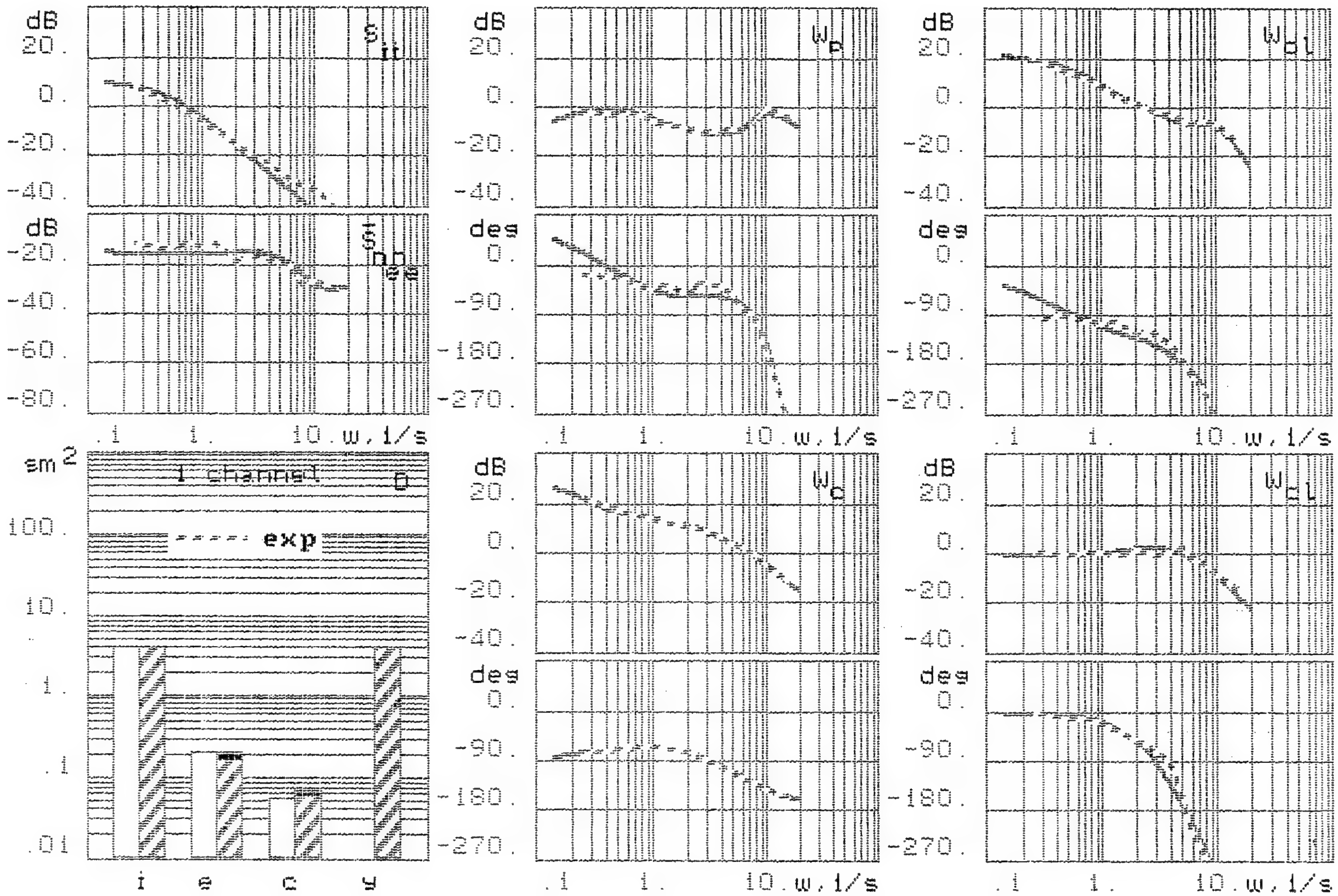


Fig.4.10. Comparison of mathematical modeling and experimental results (conf. 3-1)

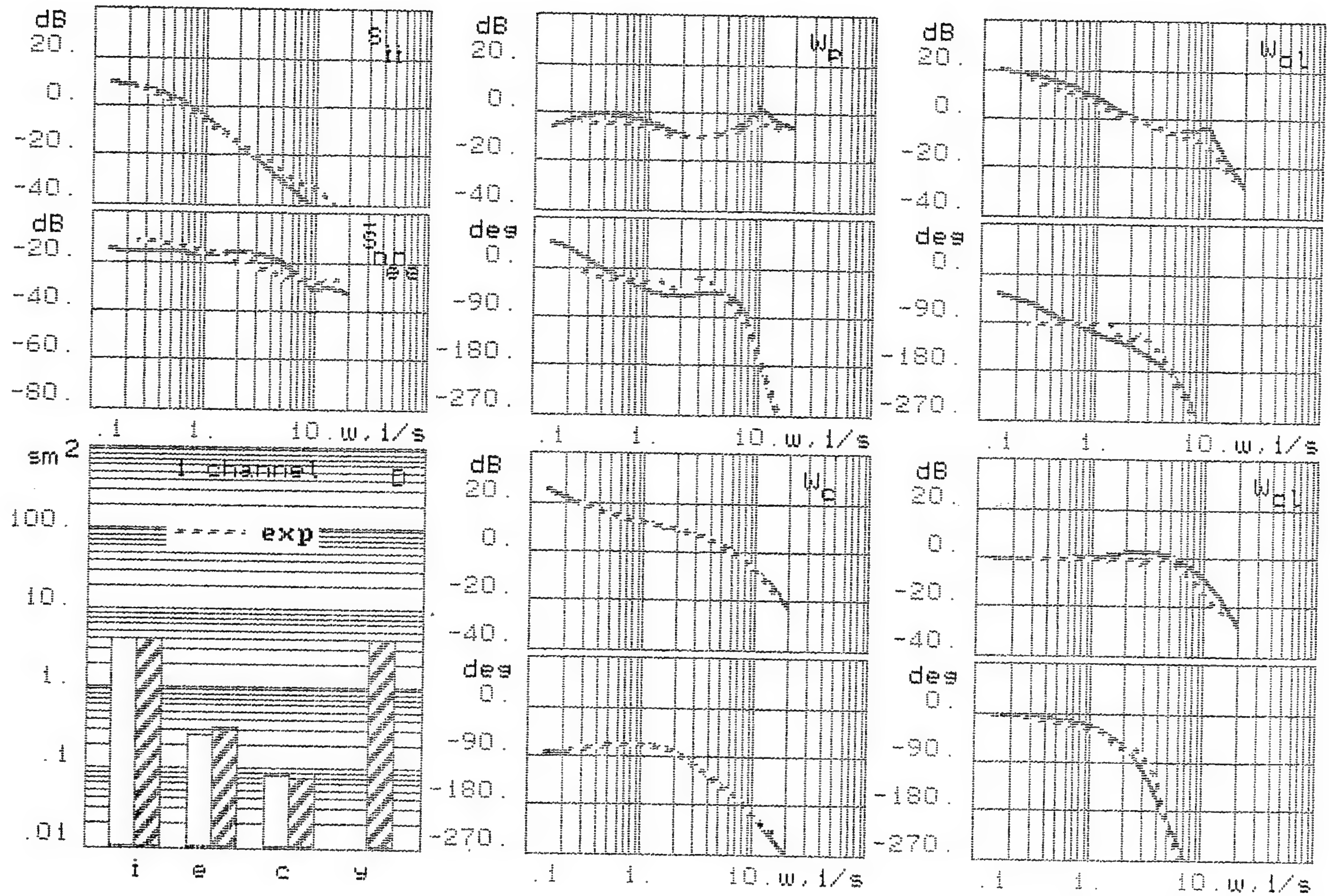


Fig.4.11. Comparison of mathematical modeling and experimental results (conf. 3-6)

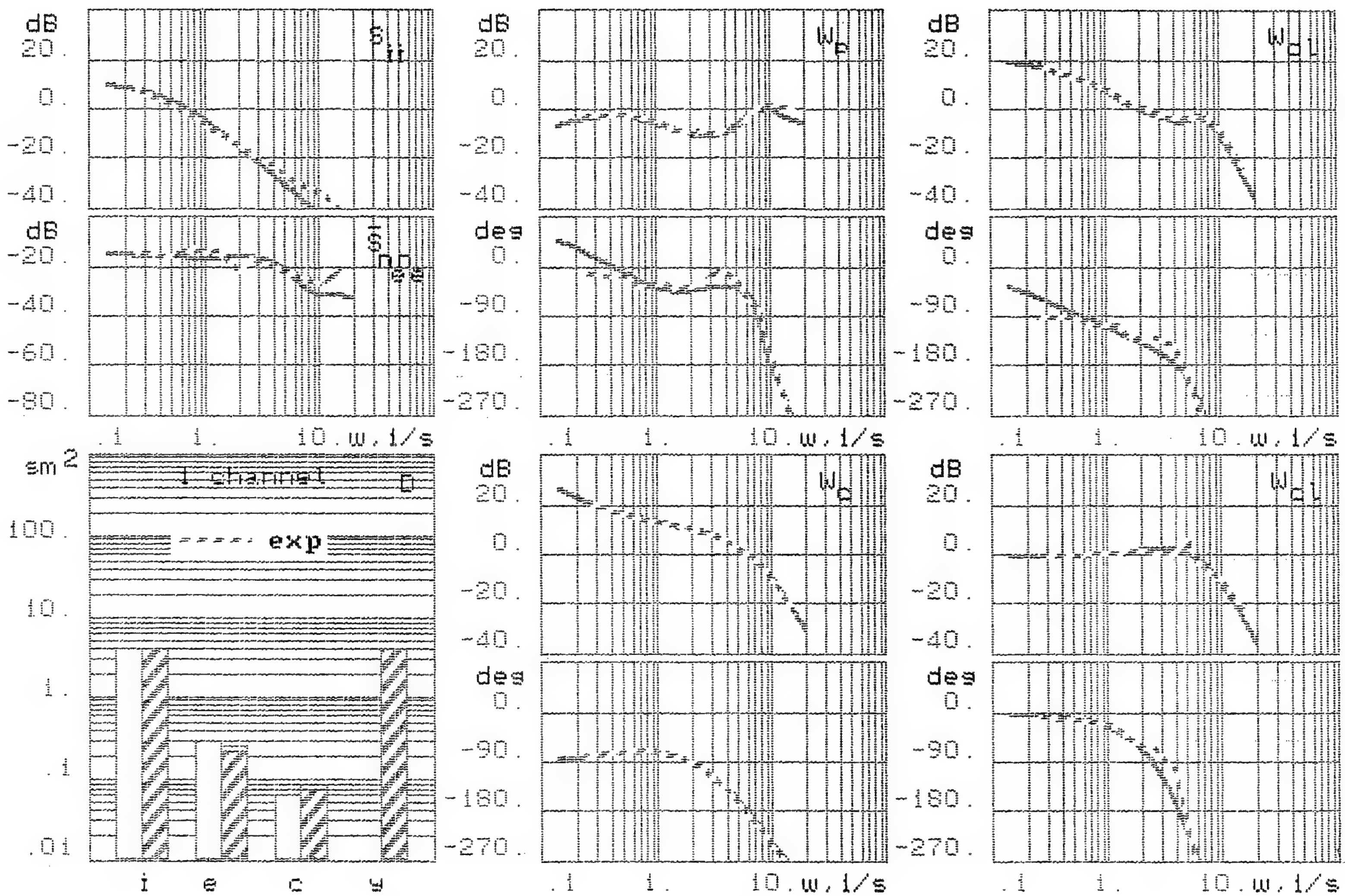


Fig.4.12. Comparison of mathematical modeling and experimental results (conf. 3-8)

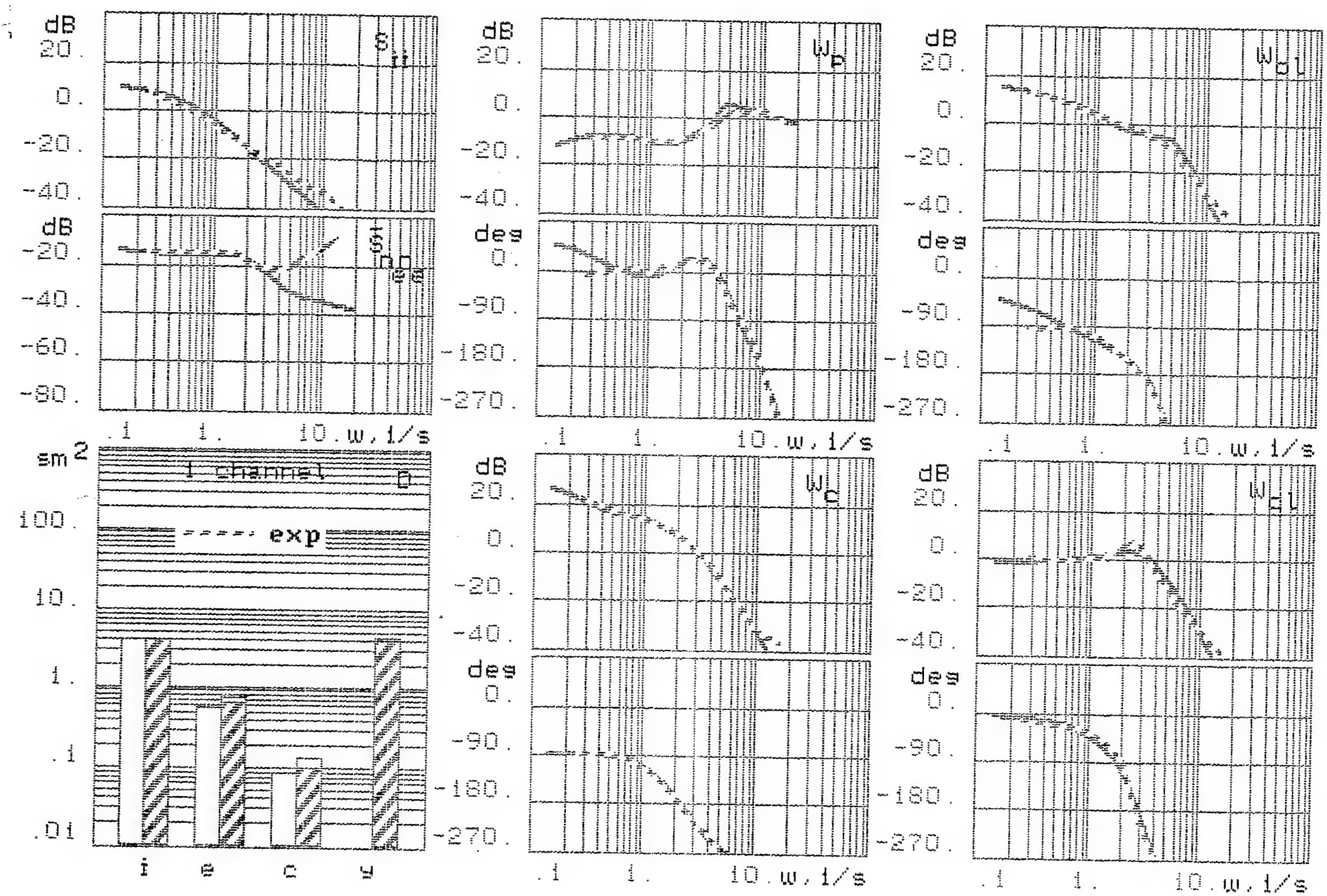


Fig.4.13. Comparison of mathematical modeling and experimental results (conf. 3-12)

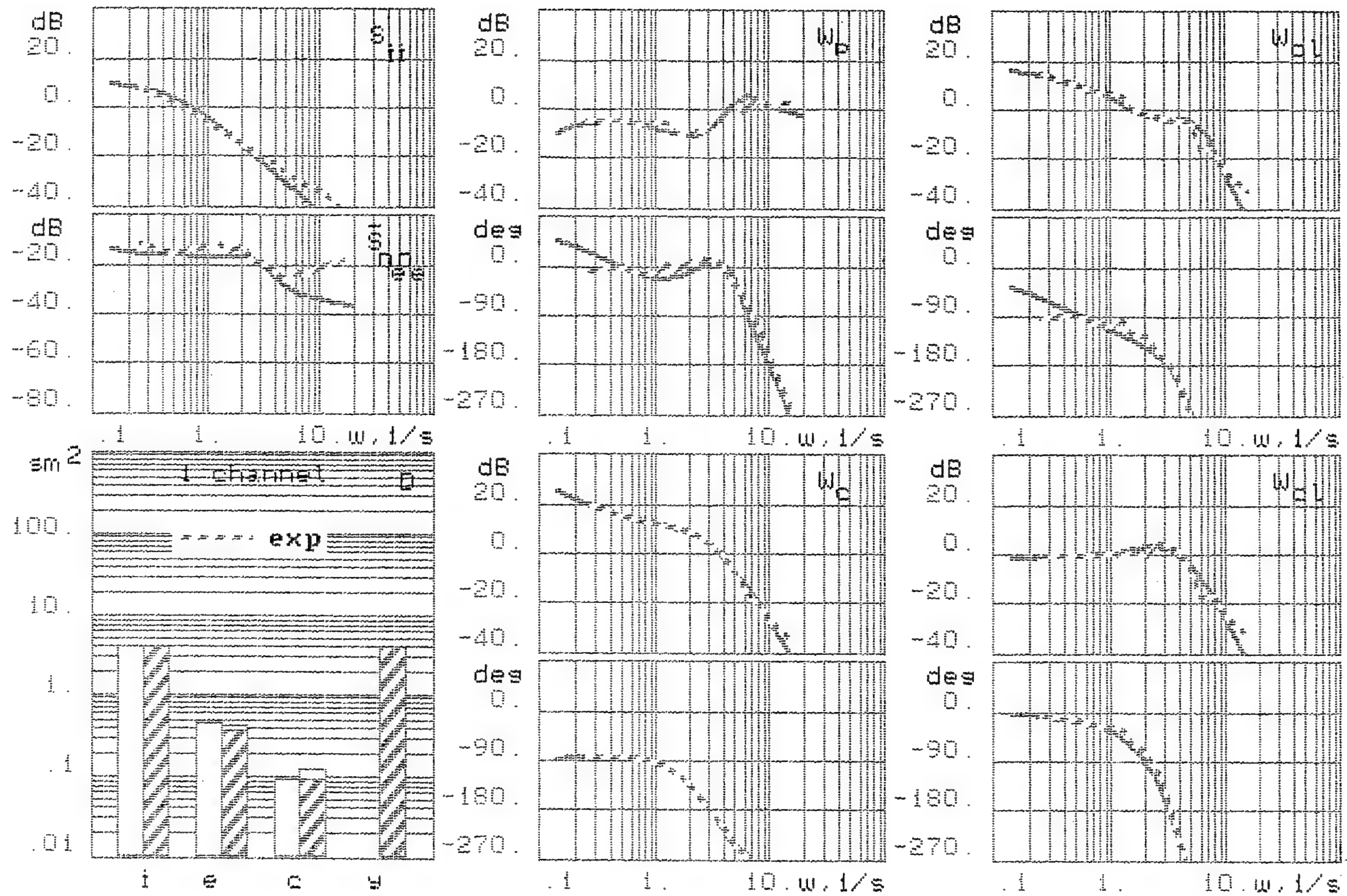


Fig.4.14. Comparison of mathematical modeling and experimental results (conf. 3-13)

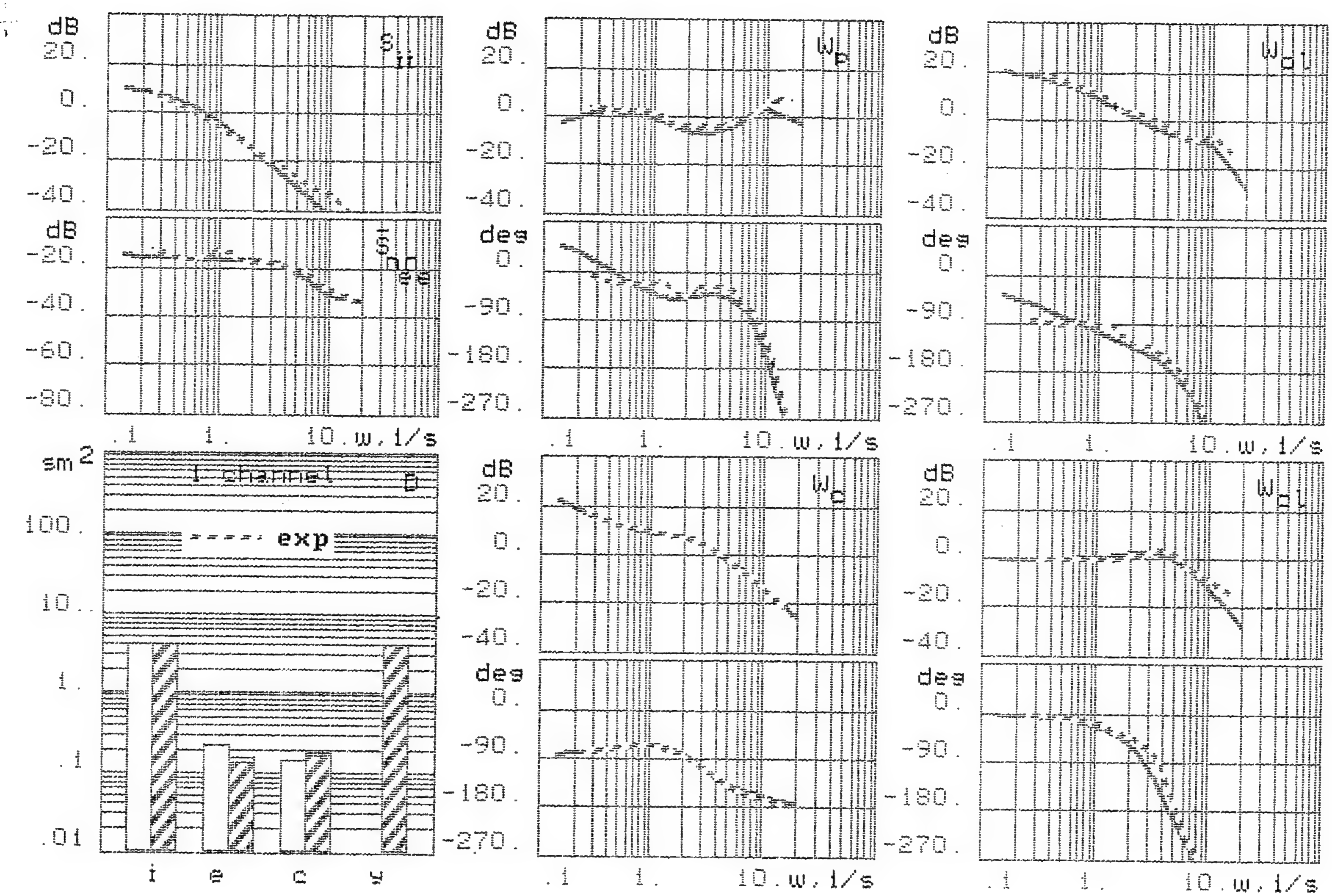


Fig.4.15. Comparison of mathematical modeling and experimental results (conf. 4-1)

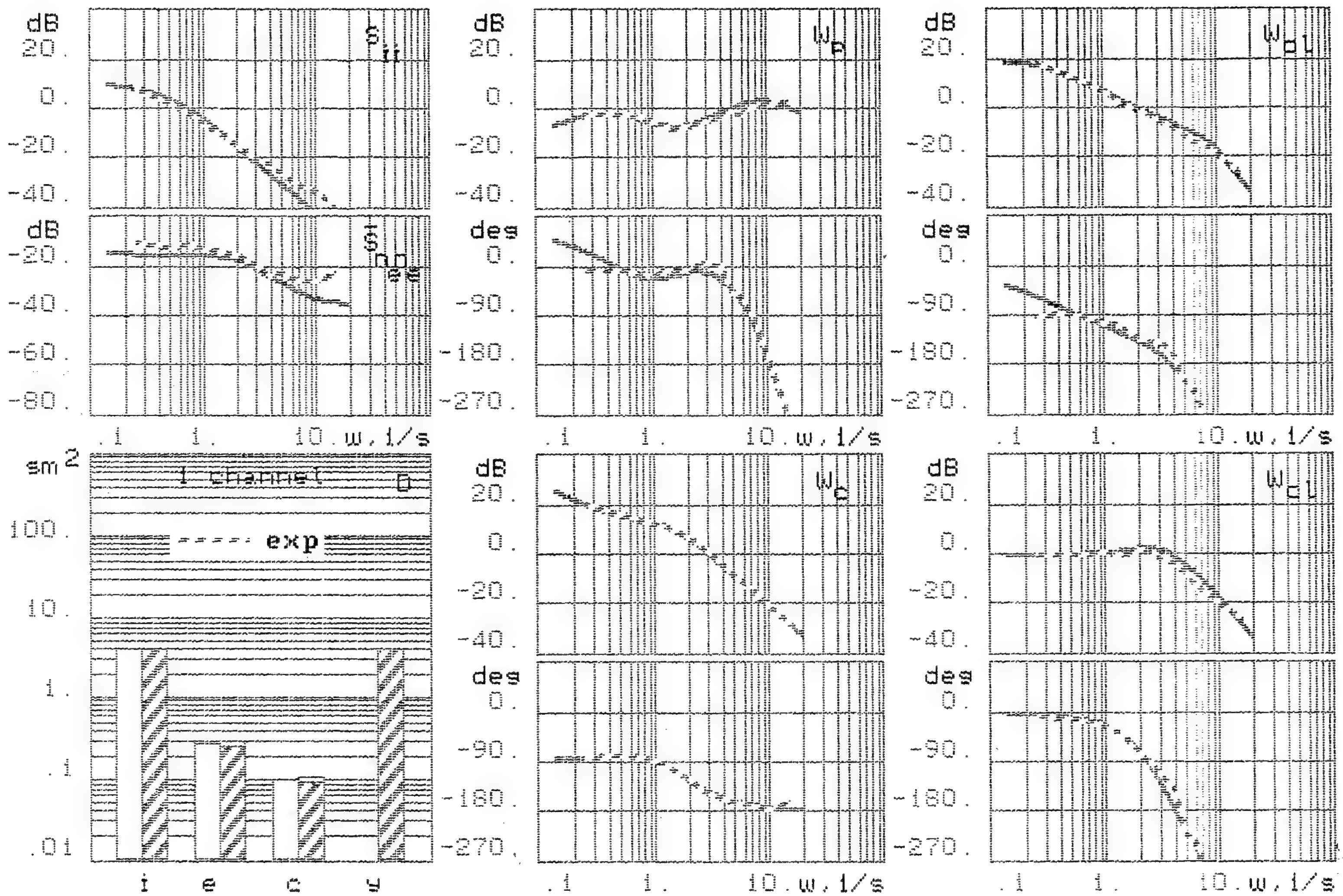


Fig.4.16. Comparison of mathematical modeling and experimental results (conf. 5-1)

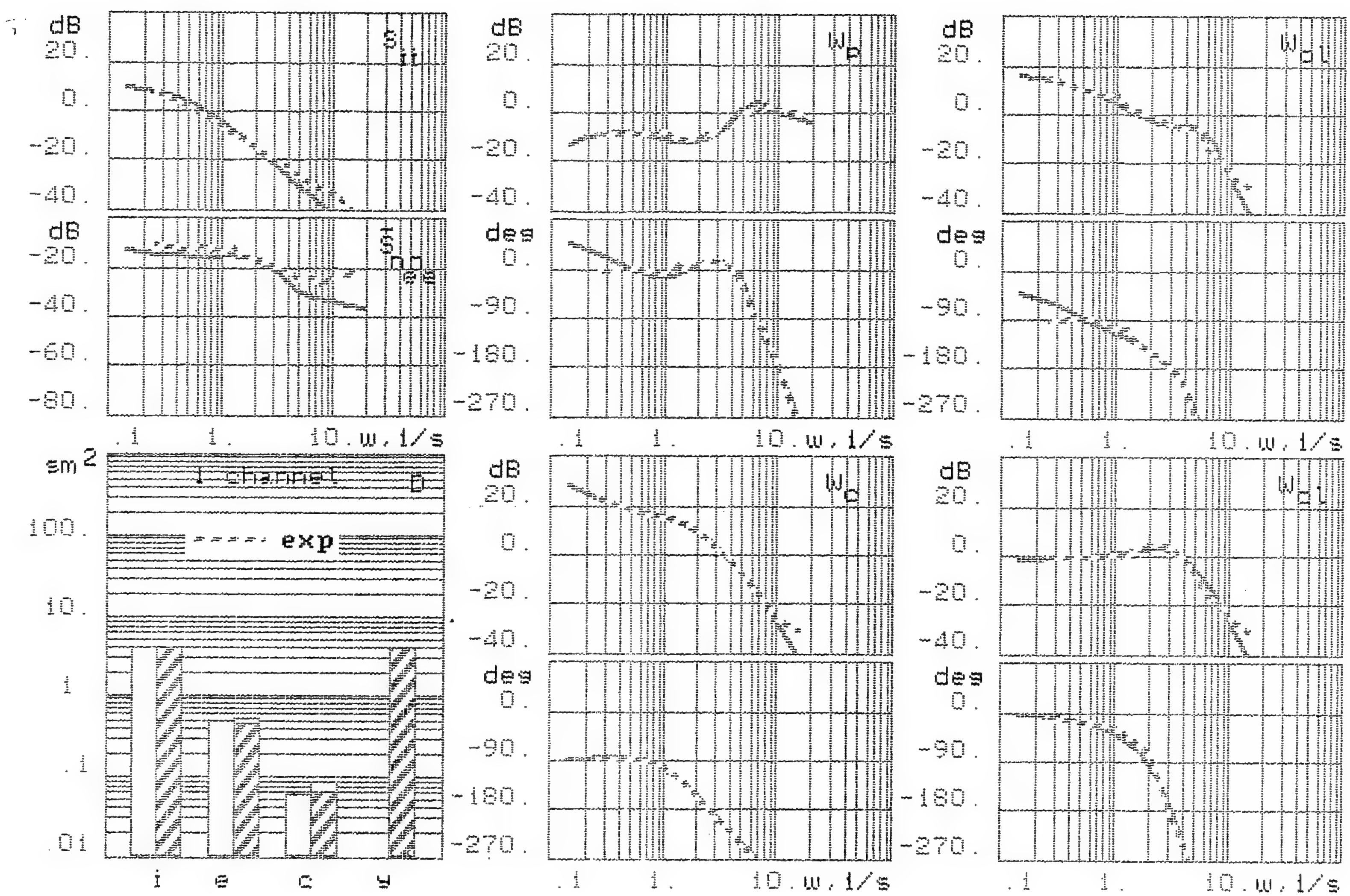


Fig.4.17. Comparison of mathematical modeling and experimental results (conf. 5-9)

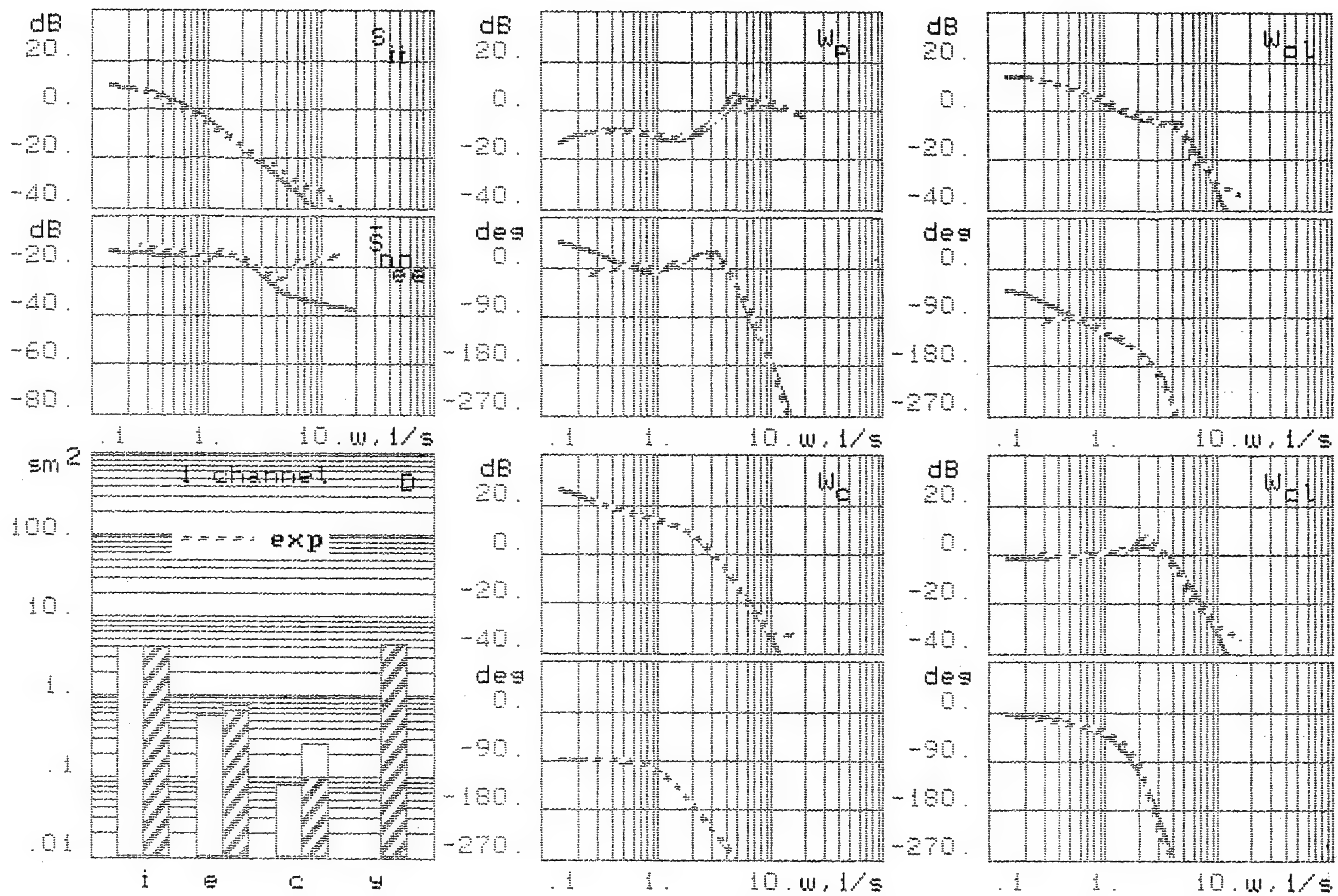


Fig.4.18. Comparison of mathematical modeling and experimental results (conf. 5-10)

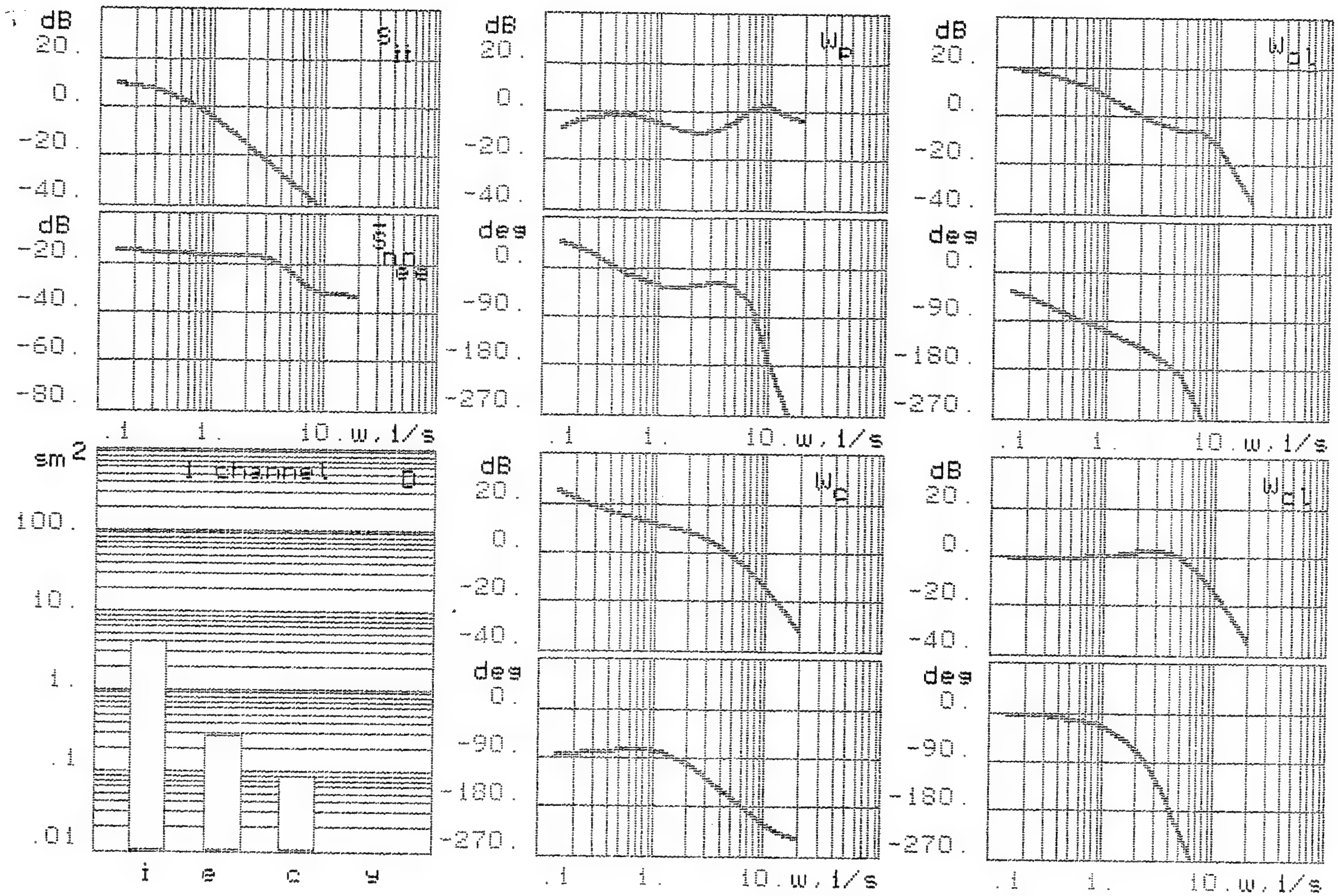


Fig.4.19. Mathematical modeling (conf. 3-3)

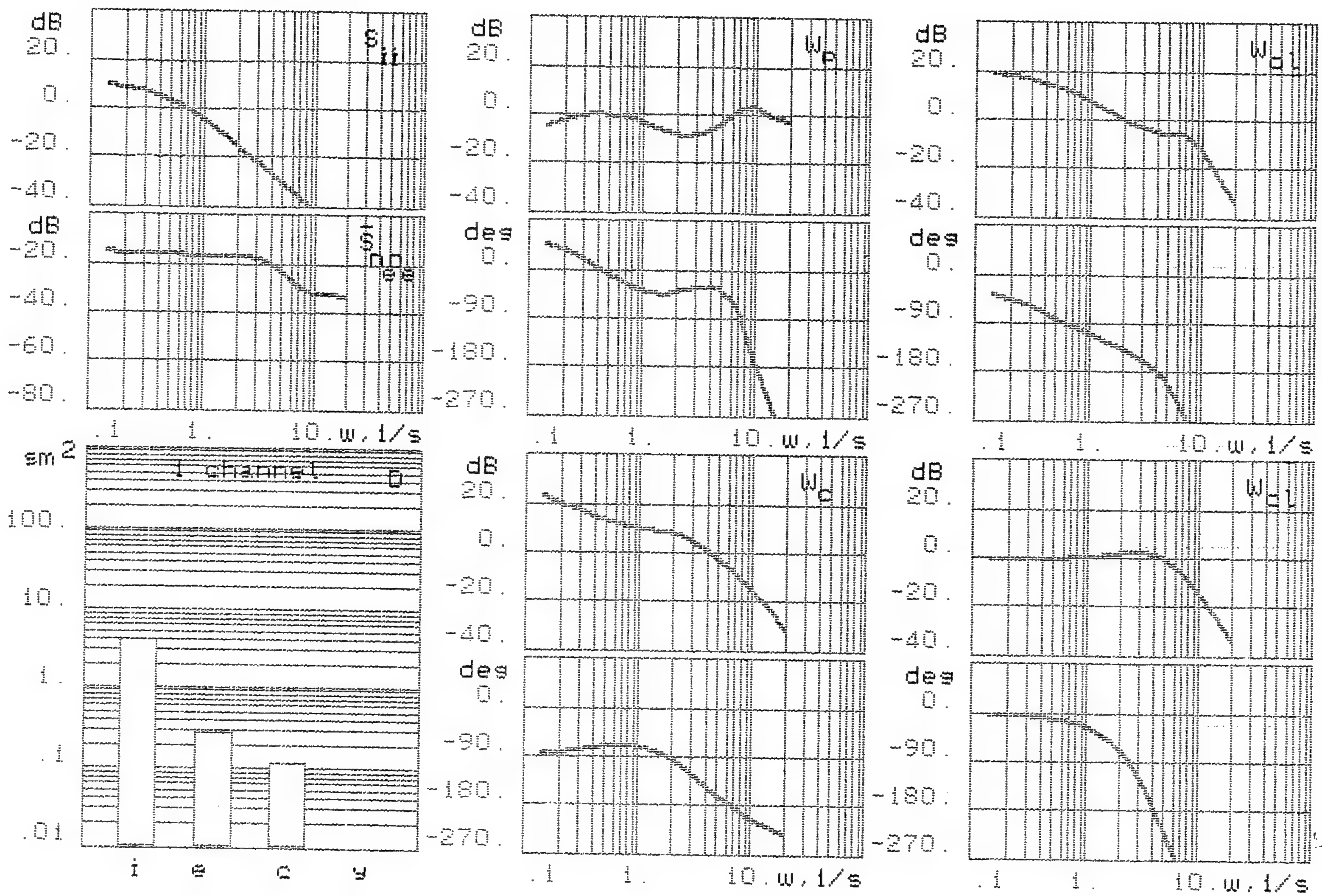


Fig.4.20. Mathematical modeling (conf. 4-2)

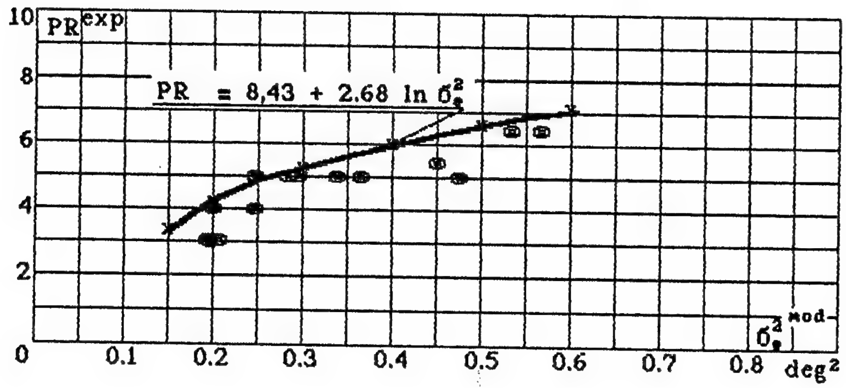


Fig.4.21. The comparison of experimental results with the equation (4.2)

b. Air-to-air tracking task

OCM was used for the definition of the lines of equal variances of error in the coordinates ξ_{sp} and ω_{sp} and theirs comparison with the lines obtained experimentally and described in chapter 1.

The mathematical model of controlled element dynamics corresponded to the equation (3.3).

The input spectral density of input signal corresponded to the following equation

$$S_{ii} = \frac{K^2}{(\omega_i^2 + 05^2)^2},$$

$$\sigma_i^2 = 4\ (\deg^2).$$

The parameters of optimal control model are given in table 4.1.

The modeling was carried out for the different combinations of ξ_{sp} and ω_{sp}. For each of them it was calculated simultaneously the optimal gain coefficient $K_{c_{opt}}$, supplied the minimum variance of error. The results of calculation for $-Z_W = 1.25$, 1/s and $-Z_W = 3.5$ 1/s are given in tables 4.3 and 4.4, on fig.4.22 and 4.23 there are drawn the lines of equal errors. The calculated pilot describing functions for a number of parameters (ξ_{sp}, ω_{sp}, $-Z_W$) are given on fig.4.24-4.30 these characteristics have good agreement with results of experimental investigations shown on these figures too.

c. Refueling task

It was considered the dual channel pilot-vehicle system. The effect of increased number of channels was taking into account with help of attention distribution parameter f_i: $\sum_{i=1}^{n} f_i = 1$, where n is a number of channels. This takes into account the increase of observation remnant level $V_{n_{e_i}} = \frac{\rho_e}{f_i}\sigma_e^2$ where the additional channel is added.

With help of OCM it was investigated the influence of controlled element in longitudinal channel on pilot-vehicle system characteristics in the other channel. For that purpose it was considered two types of FCS in longitudinal channel - RCAH and

$\sigma_e^2(\text{OCM}) = f(\xi,\omega)$ for $-Z_W = 1.25$, 1/s

Table 4.3

ξ / ω, 1/s	0.286	0.3	0.5	0.7	1.0	1.5	2.0
1.0	-	-	-	-	0.1672	-	-
1.2	-	0.1886	-	-	-	-	-
1.225	-	-	-	0.1634	-	-	-
1.25	-	-	0.1710	-	-	-	-
1.5	-	-	-	-	-	0.1357	-
1.75	-	-	-	-	0.1372	-	-
2.0	0.1646	-	0.1488	-	-	-	0.1196
2.5	-	-	-	-	0.1246	-	-
2.625	-	-	-	-	-	0.1157	-
3.5	-	-	0.1395	-	-	-	-
4.0	-	-	-	-	0.1170	-	-
5.0	-	-	-	-	-	-	0.1001
7.0	-	-	-	-	0.1187	-	-
8.0	-	-	-	-	-	-	0.1034
10.5	-	-	-	-	-	0.1088	-

$\sigma_e^2(\text{OCM}) = f(\xi,\omega)$ for $-Z_W = 3.5$, 1/s

Table 4.4

ξ / ω, 1/s	0.3	0.5	1.0	1.5	2.0
1.25	-	0.2528	-	-	-
2.0	-	0.1870	-	-	-
2.5	-	-	0.1465	-	-
3.0	0.1723	-	-	-	-
3.5	-	0.1454	-	-	-
4.0	-	-	0.1225	-	-
5.0	-	0.1356	-	-	0.1066
7.0	-	-	0.1075	-	-
8.0	-	-	-	-	0.0967
10.5	-	-	-	0.0928	-
14.0	-	-	-	-	0.0896

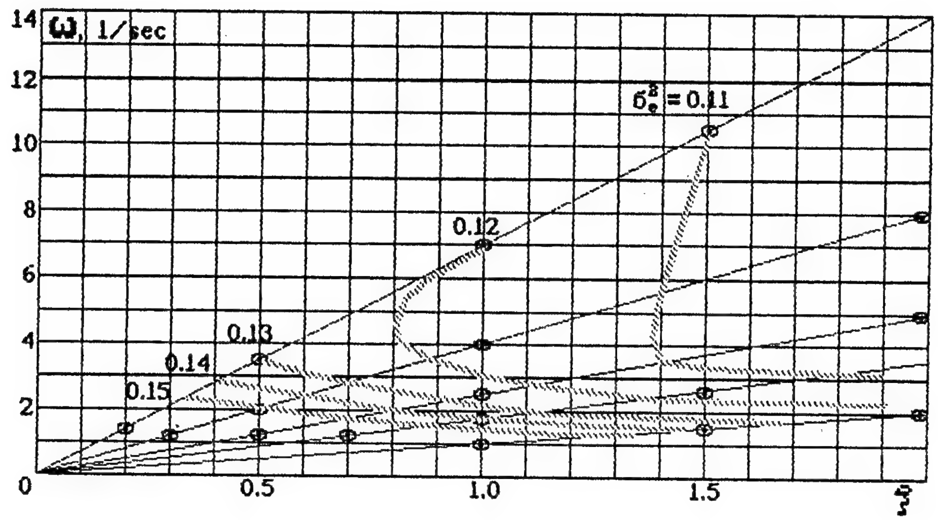


Fig.4.22. The lines of equal variances σ_e^2 (for $-Z_W=1.25$[1/S])

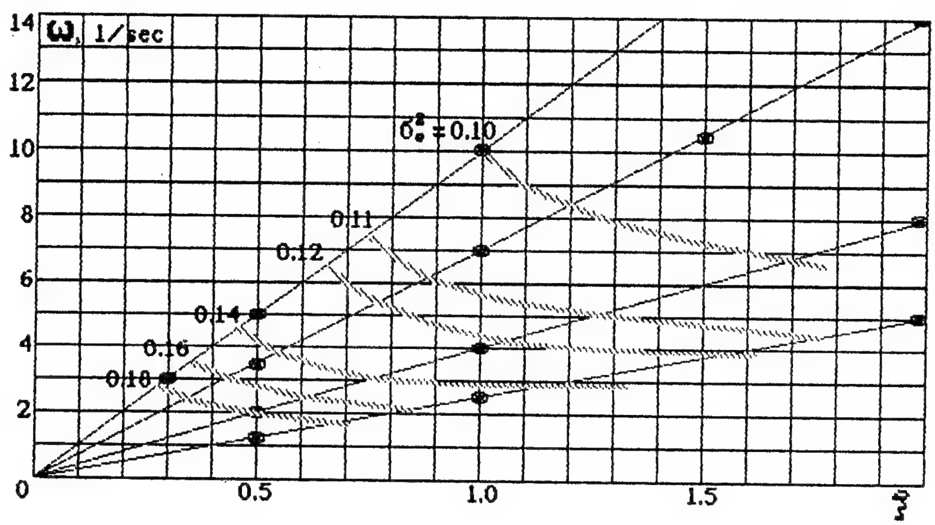


Fig.4.23. The lines of equal variances σ_e^2 (for $-Z_W=3.5$[1/S])

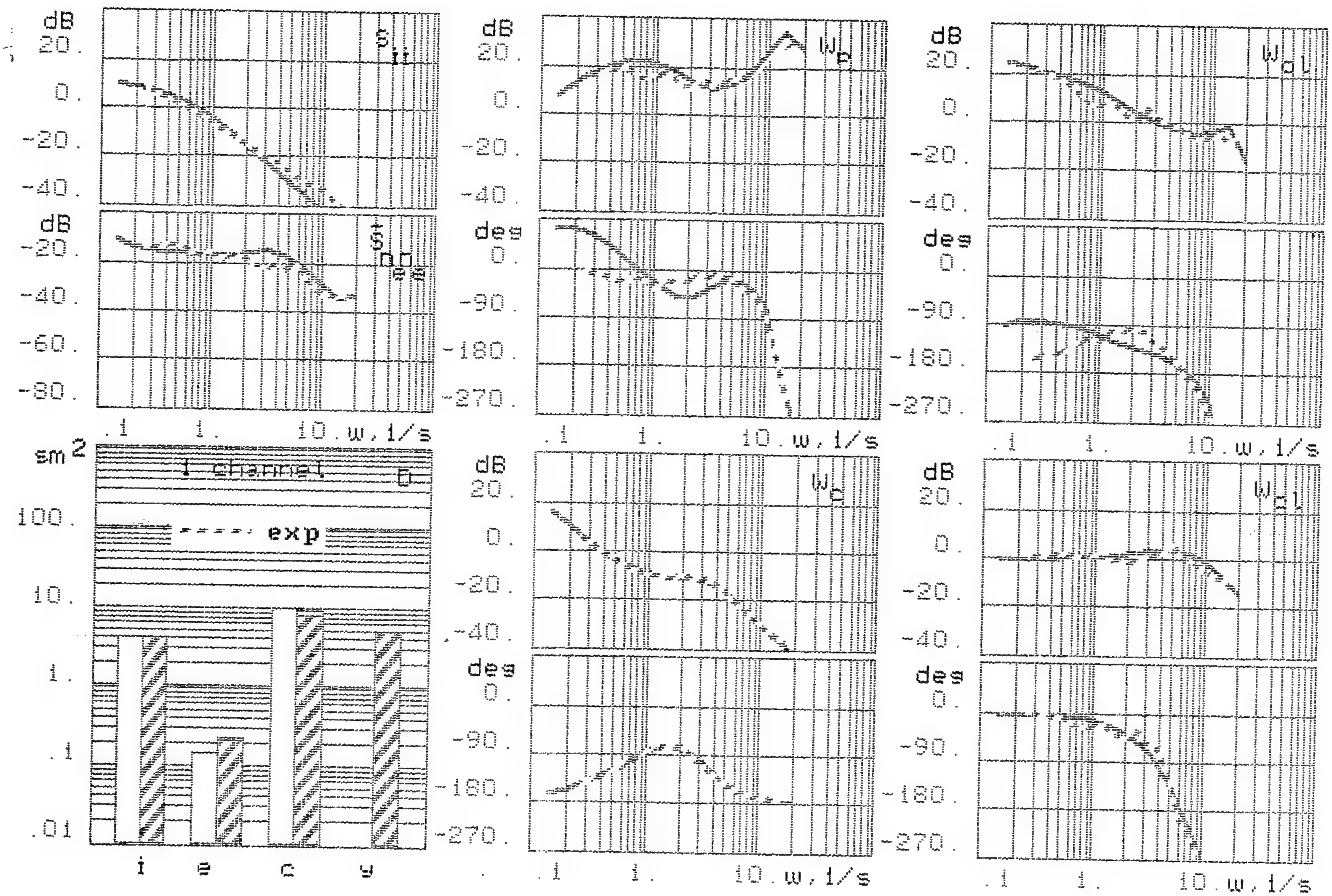


Fig.4.24. Comparison of mathematical modeling and experimental results for $\omega_{sp}=7$ 1/sec, $\xi_{sp}=1$, $-Z_w=1.25$ 1/sec

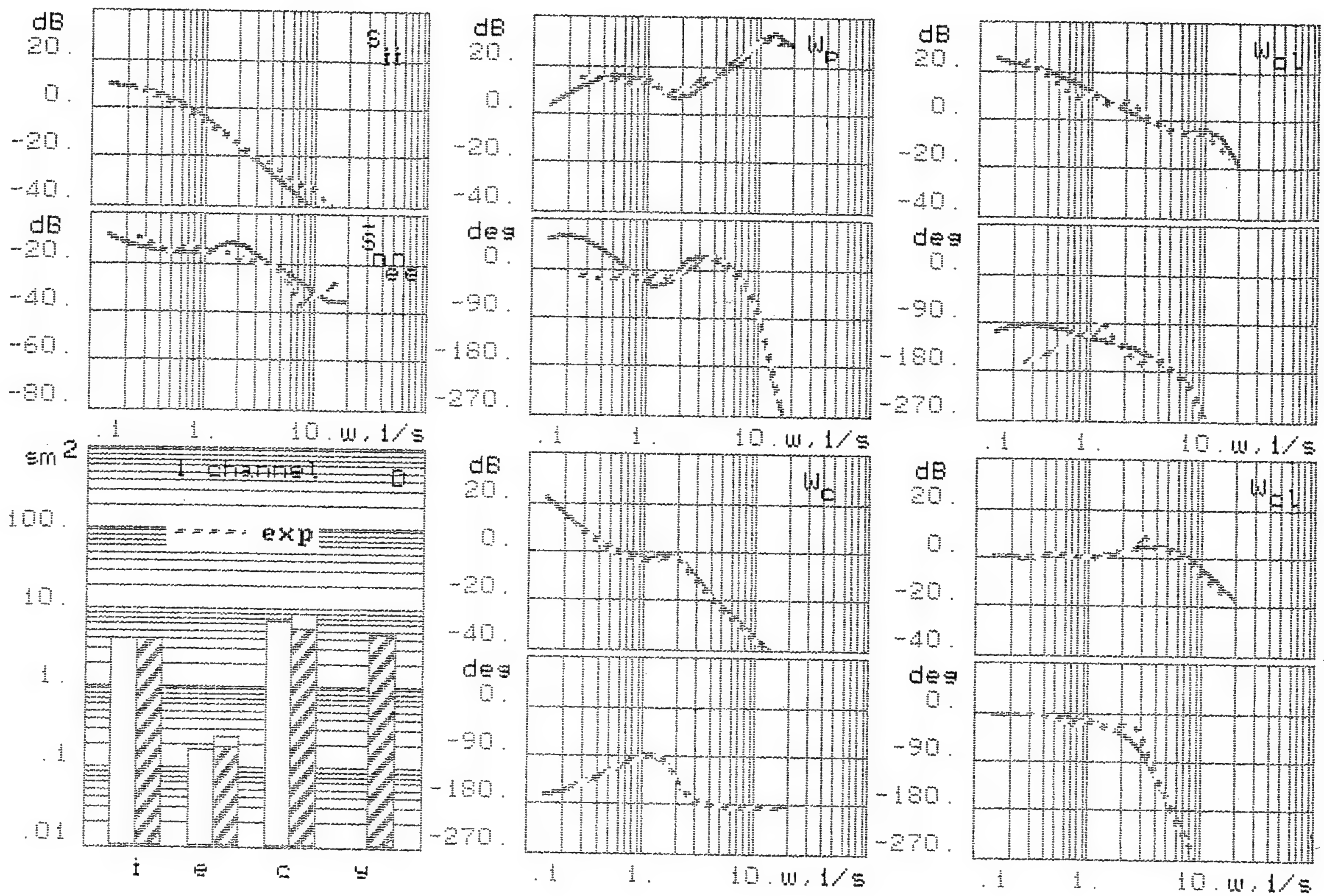


Fig.4.25. Comparison of mathematical modeling and experimental results for $\omega_{sp}=2$ 1/sec, $\zeta_{sp}=0.286$, $-Z_w=1.25$ 1/sec

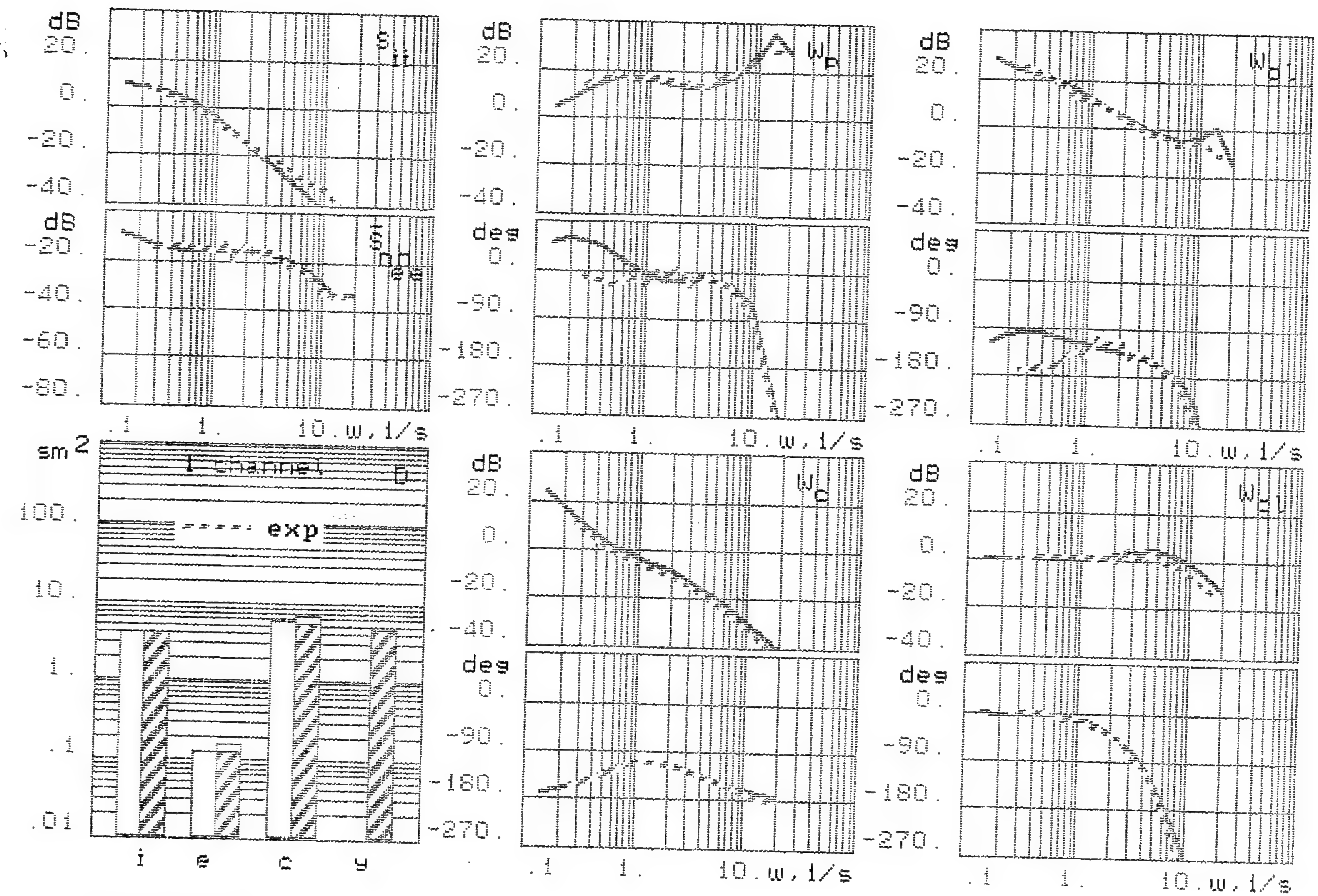


Fig.4.26. Comparison of mathematical modeling and experimental results for $\omega_{sp} = 2.5$ 1/sec, $\xi_{sp} = 1$, $-Z_w = 1.25$ 1/sec

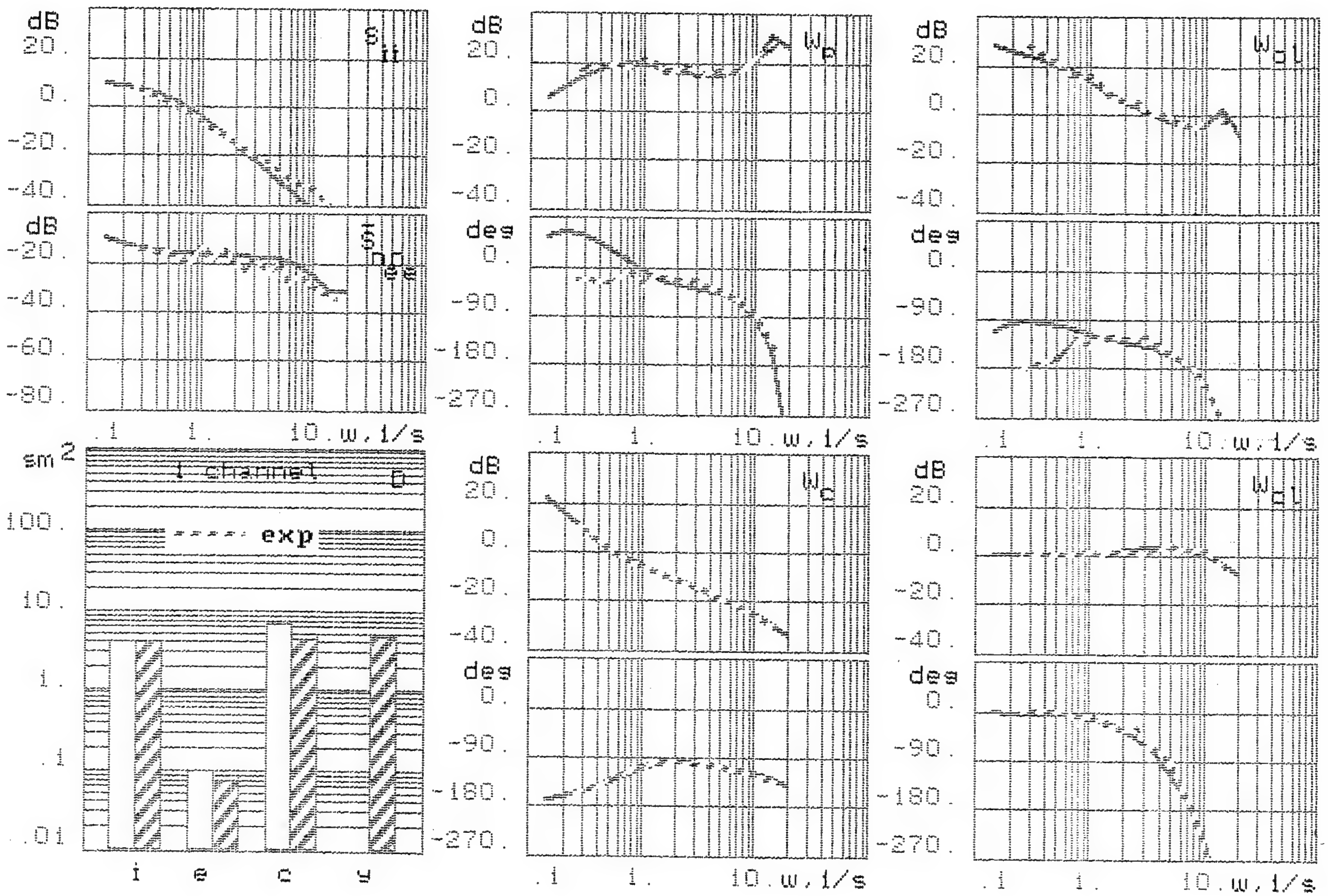


Fig.4.27. Comparison of mathematical modeling and experimental results for $\omega_{sp} = 5$ 1/sec, $\xi_{sp} = 2$, $-Z_w = 1.25$ 1/sec

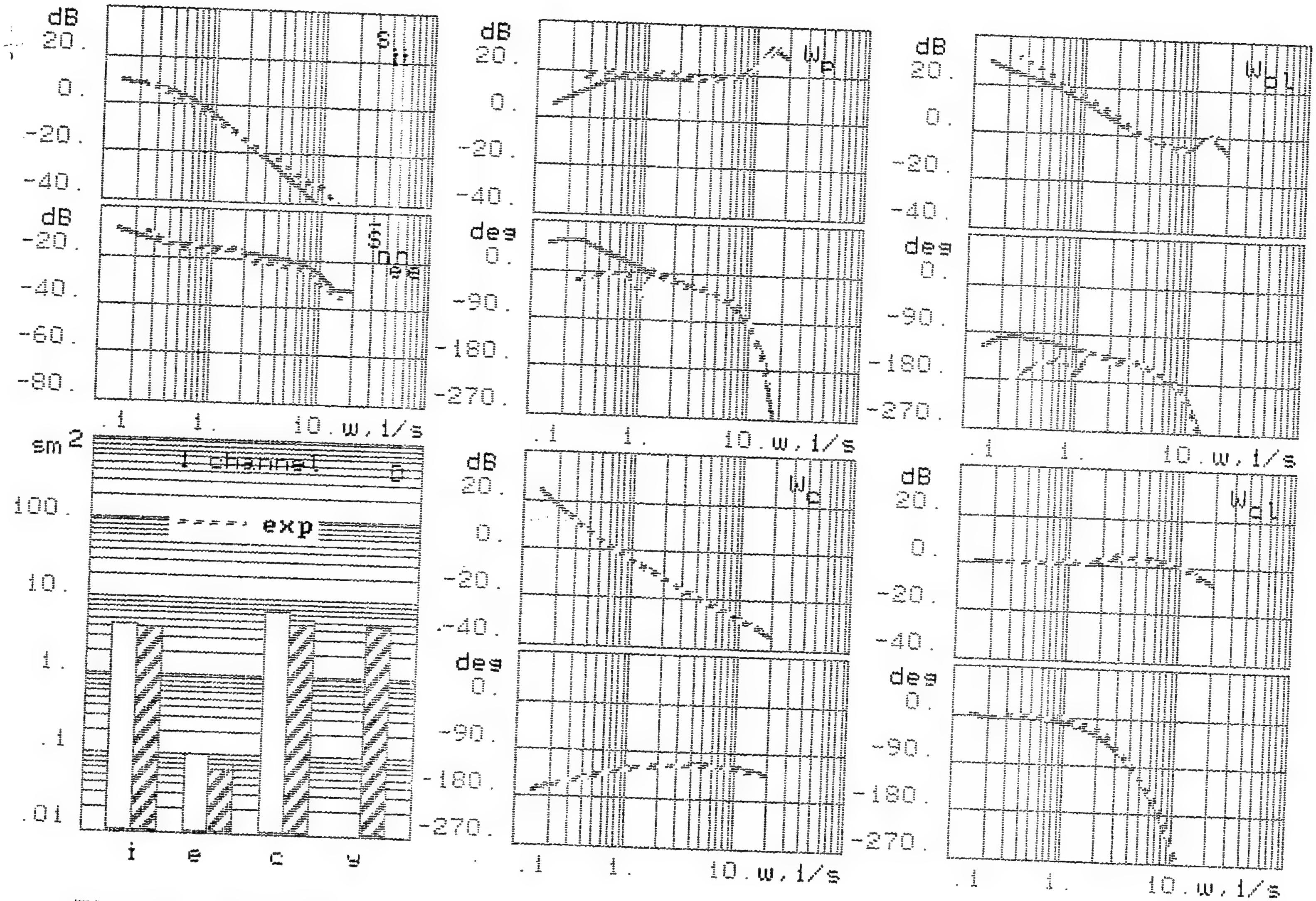


Fig.4.28. Comparison of mathematical modeling and experimental results for $\omega_{sp} = 8$ 1/sec, $\xi_{sp} = 2$, $-Z_w = 3.5$ 1/sec

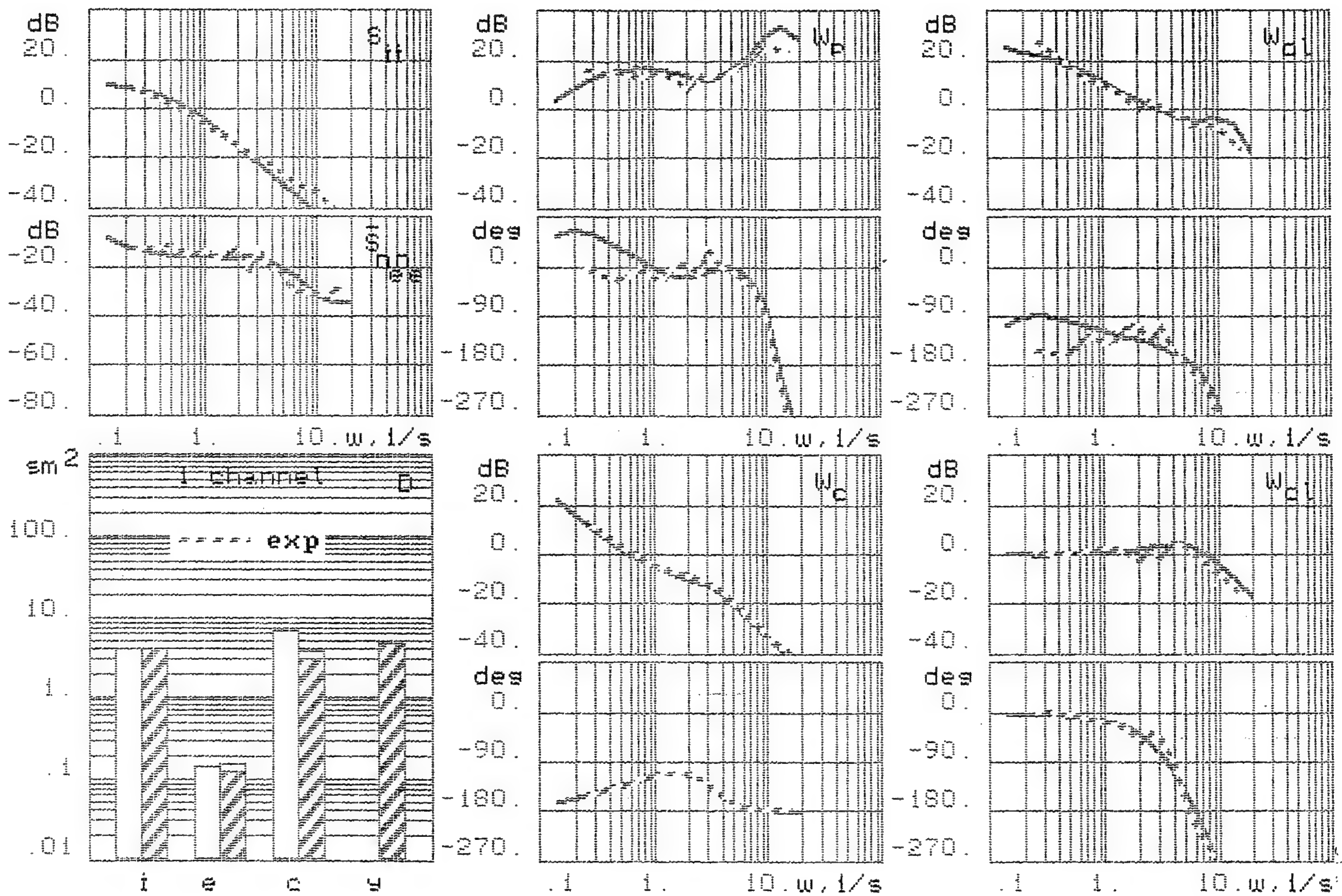


Fig.4.29. Comparison of mathematical modeling and experimental results for $\omega_{sp} = 3.5$ 1/sec, $\zeta_{sp} = 0.5$, $-Z_w = 3.5$ 1/sec

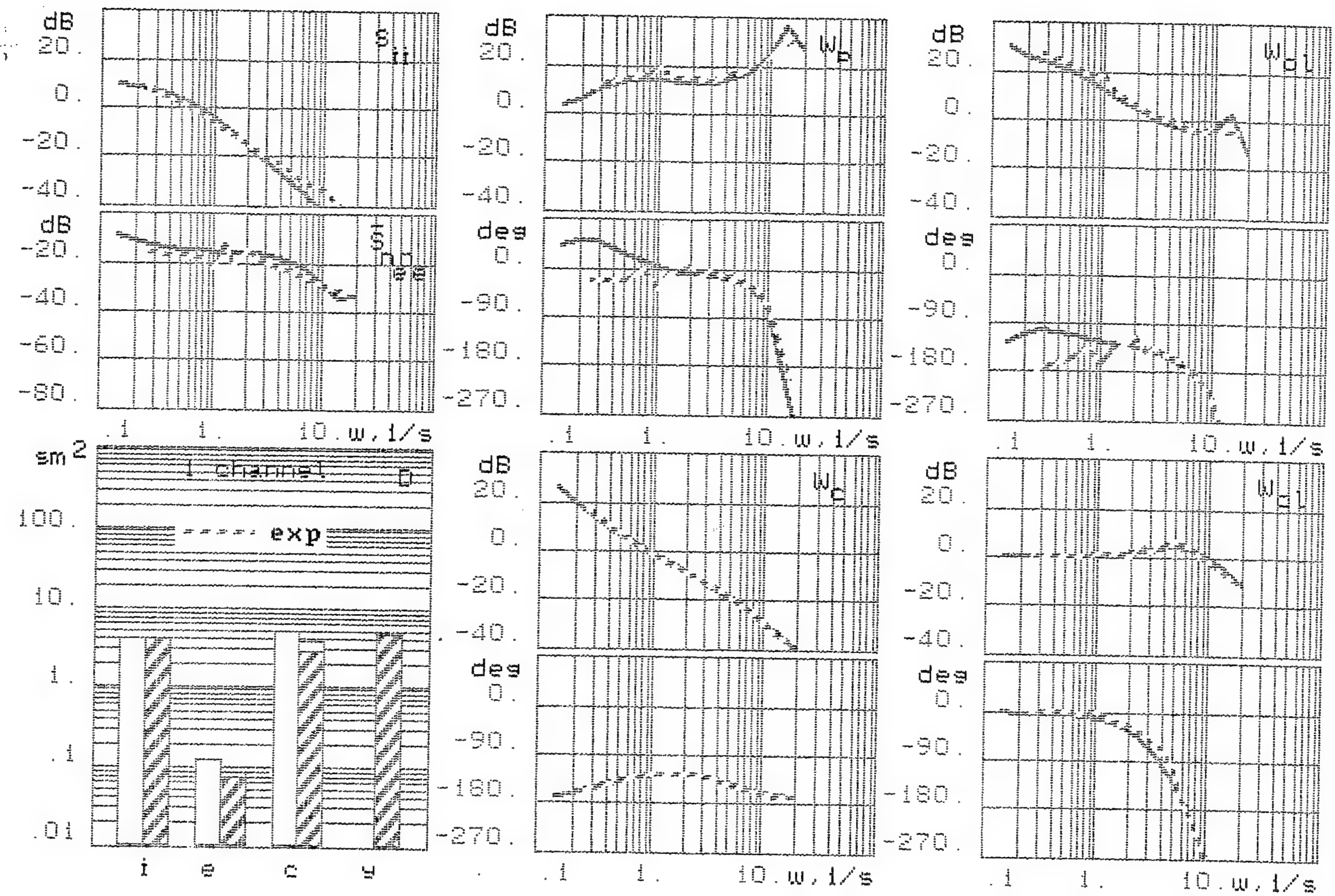


Fig.4.30. Comparison of mathematical modeling and experimental results for $\omega_{sp}=4$ 1/sec, $\zeta_{sp}=1$, $-Z_w=3.5$ 1/sec

ACAH. The transfer function for controlled element dynamics in this channel is the following

$$W_c = W_{pr} W_\theta W^{\varepsilon\theta}$$

where $W_{pr} = 1$ for RCAH type of FCS

$W_{pr} = \frac{Ts}{Ts+1}$ for ACAH type of FCS.

The transfer functions W_θ and $W^{\varepsilon\theta}$ correspond to the equations (1.6) and (3.).

The transfer function for controlled element dynamic in lateral channel can be obtained by use the equations (3.4) (3.6) and taking into account the bank feedback and. It is the following

$$W_{c_D} = \frac{\varepsilon_L}{\delta_a} = \frac{K_p(s+V/L)(s-Z_W)}{s^2(\frac{T\phi}{K_\phi}s^2 + \frac{1}{K_\phi}s+1)}$$

where for longitudinal channel

$\omega_q = -Z_W = 1.25;$

$\xi = 0.7,\ \omega_a = 4.9;$

V = 100 m/s, L = 5m,

for lateral channel

$T_\Phi = 0.25$ s, $K_\Phi = 2$

T = 0.2 s.

By use the OCM it was calculated variances $\sigma^2_{\varepsilon_V}(f)$ (for ACAH and RCAH system), $\sigma^2_{\varepsilon_L}(1-f)$ where f = 0.2 ÷ 0.8, and $\sigma^2_\Sigma = \sigma^2_{\varepsilon_V} + \sigma^2_{\varepsilon_L}$. The results of mathematical modeling shown on fig.4.31 demonstrated that the different types of systems correspond to the different value of f.

It was shown also that the improvement of flying qualities in longitudinal channel (use of ACAH system) causes the decrease of variance of error in longitudinal and in lateral channel too. This results corresponds to results of experimental investigations.

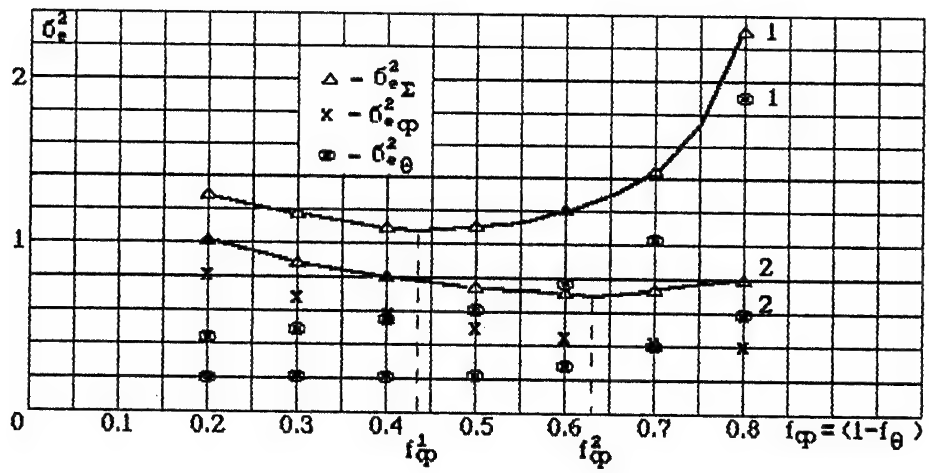


Fig.4.31. Results of mathematical modeling of dual channel refueling task

GENERAL CONCLUSSIONS

In this report the following research were fulfilled

- analysis of problems in use of the standards for flying qualities of requirements and criteria for their prediction,

- development of technique for evaluation of flying qualities,

- development of criteria for evaluation of flying qualities based on standardization of pilot-vehicle system characteristics for a number of piloting tasks,

- modification of human operator optimal model.

The main results are the following:

A. Exposed problems in standartization and use of criteria for evalulution of flying qualities:

- Apperance of new types of vehicles noncoresponded to the known classes of aircraft.

- Nonoptimum way in choose of flying qualities for each piloting task by use the requirements developed for flight phases.

- Variability and dtfficulties in evaluation of flying qualities in investigated piloting task due to uncertainty of key parameter of Cooper-Harper sxale - task performances and pilot complusation.

- Imposibility to use the carrent requrements for evaluation of flying qualities for highly augmented aircraft with new types of responses and nontraditional side effects.

- Bad accordance between the known requirements to aircraft dynamic parameters and requirements followed from the investigation of tracking tasks.

- Low potentiality of know-criteria developed from pilot-vehicle consideration for prediction of flying qualities.

B. Developed system approach for decision of different manual control tasks and definition of main problems in creation of criteria for flying qualities on basis of system approach.

C. The technique for evaluation of flying qualities in tracking piloting tasks. There were: Developed

- the technique for definition of pilot rating as a function of Flying Qualities Parameter and obtained the rules for use of this function in case when the Task Desired Flying Qualities is determined by the conditions of fulfilment of concrete tracking piloting task.

- the function $PR = F(J_{des}, J_{opt}, J)$ for compensatory tracking tasks. On basis of this function there are defined the relations for determination of desired and adequate task performances supplied the equal PR for different input spectral density. It was also checked the function PR = f(Flying Qualities Parameters) in experiments with Neal-Smith and HAVE PIO configuration and demonstrated good agreement of results.

D. The modified criteria for prediction of flying qualities and PIO tendency in pitch tracking task.

- The criteria based on standardization of the following parameters: normalyzed resonance peak $\bar{r} = r / r_{opt}$ and pilot compensation parameter ($T^{*}_{lead} = \frac{\Delta\varphi^{+}}{\omega_1}$, or $T^{*}_{lag} = \frac{\Delta\varphi^{-}}{\omega_2}$).

- The criteria was tested for a wide data base including 23 Neal-Smith, 25 LAHOS and 16 HAVE PIO configurations. All experiments demonstrated good agreements with proposed boundaries.

E. The criteria for evaluation of flying qualities for probe and drogue refuling task.

- The criteria bases on investigation of 9 Neal-Smith and 12 HAVE GAS configurations.

- The developed technique for evaluation of flying qualities allowed to get the desired and adequate task performances for refueling tasks.

F. Wide investigations of influence of task variables on pilot-vehicle system in refueling task exposed

- The considerable influence of distance between pilot and drogue on different task variables causing the change of pilot-vehicle system characteristics.

- Considerable potentialities of FCS supplied ACAH type of response in lateral and longitudinal channels at the final stage of refueling.

- The higher potentialities of aircraft with conventional type of response in comparison with RCAH type in refueling and the opposite effect in air-to-air tracking task.

For aircraft with conventional type of response the accuracy in refueling increases for decreasied danping ratio.

- Some peculiarities of human behavior in refueling:

a. The possibility to close the additional inner loop in case of high values of varianses of backet displasment or controlled element gain coefficient.

b. The usade of information about the linear (not angular) coordinate defined the position between probe and drogue at the last stage of refueling.

G. The modification of pilot behavior OCM. The modifications allowed:

- to improve the agreement between the experimental and mathematical modelling results,
- to optimize controlled element gain coefficients,
- to spread the potentiality of model in explanation of peculiarities of pilot behavior,
- to decide the problem in choose of weighting coefficients in cost function for singleloop compensatory tasks.

H. Wide use of OCM in decision of different piloting tasks:

- air-to-air tracking task,
- pitch tracking task,
- refueling task.

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